Design of a Small-Scale, Low-Cost Cold Storage System

Local Roots
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BE 487: Biosystems Design Project

Executive Summary

Dr. John Biernbaum plans to add an energy efficient cold storage unit to the Student Organic Farm (SOF). The Local Roots team was tasked with designing the cold storage unit. Efficient cold storage enables farmers to provide pristine produce year round to purchasers at a low energy cost. Proper cooling and storage of produce is as essential to a farm's success as growing quality produce is. The Local Roots team was provided with the storage loads, and was asked to design an aboveground and a basement cold storage unit.

Using the maximum produce load of 32,250 lbs, and the storage containers required to accommodate the load, the dimensions of the room were determined. The range of produce can be stored using two different room conditions. One room will be cool and dry with a temperature range between 50-60 F and 60-70% relative humidity. The other room will be cold and damp with a range of 36-40 F and 85-95% relative humidity. The dimensions of the large room were calculated to be 35ft x 25ft and the small room is 21ft x 17ft. Each room is 8 ft tall.

Instead of having two equal sized rooms, it was determined to be more efficient to have a large room and a small room, switching which room would have the cool or cold produce depending on the season. The large room would store the cold produce in summer and the cool produce in winter. The small room would store the summer cold and fall cool produce. An electronic controller will be used to change the temperatures of the room between seasons.

The total heat load of the unit was analyzed. This is composed of field heat, heat from respiration, heat from conduction through the walls and heat generated from electrical components and workers moving in and out. The maximum heat load for the cold room was determined to be 14,322 BTU/hr and 9,427 BTU/hr for the cool room.

Using the maximum heat load information, the refrigeration and ventilation designs were evaluated. A CoolBot controller system attached to the AC unit was selected as the supplemental refrigeration system. A ventilation system with evaporative cooling was selected for the ventilation system. Fiberglass and polystyrene were selected for the insulation, with a total R-value of 34.

An economic evaluation was conducted. The total cost for the basement storage unit is $51,260 and the yearly savings are $19,226, resulting in a payback period of 3.3 years. The savings derive from the reduction in electricity usage compared to the current cold storage unit. In addition to the costs of the room, the costs of an aboveground modular storage container were included. The aboveground storage costs $33,340 with a payback of 2.4 years. While the basement saves $250/yr on electricity costs the construction costs do not justify building below ground with such a high R-value. Therefore it is concluded that the client should construct a basement below the pole barn at the SOF and build a cold storage unit within it.

Acknowledgments

Local Roots would like to thank Dr. Reese and Dr. Kirk for their dedication to helping with our project. We also would like to thank our faculty advisor, Dr. Harrigan, for the time he spent working with our team. Special thanks are extended to our client, Dr. Biernbaum, for all of the suggestions and meetings at the SOF, as well as the opportunity to work on this project. We would also like to thank Todd Forbush and Techmark for his help with the ventilation system. Local Roots also would like to thank Dennis Welch for his help with the construction cost estimates. The SOF deserves a thank you for sourcing and calculating the farm's peak storage requirements, as does Titus Farms for allowing us to visit their farm and observe how cold cellars function. Lastly we thank all professors and company representatives who throughout the year gave seminars and informational presentations on how to be a functioning, ethical and productive engineer.

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Nomenclature

$A =$ Area of wall $\left(ft^2\right)$

$HF_{coefficient} =$ Produce heat field coefficient $\left(\frac{Btu}{lb \times {}^\circ F \times hr}\right)$

$HR_{coefficient} =$ Produce heat of respiration $\left(\frac{Btu}{lb \times 24 hrs}\right)$

$Q_{Ceiling} =$ Rate of heat loss through ceiling $\left(\frac{Btu}{hr}\right)$

$Q_{Floor} =$ Rate of heat loss through floor $\left(\frac{Btu}{hr}\right)$

$Q_{FH} =$ Rate of heat loss through field heat $\left(\frac{Btu}{hr}\right)$

$Q_{HR} =$ Rate of heat loss through heat of respiration $\left(\frac{Btu}{hr}\right)$

$Q_{InteriorWall} =$ Rate of heat loss Interior Wall $\left(\frac{Btu}{hr}\right)$

$Q_{WallUpper} =$ Rate of heat loss through upper section of Basement Wall $\left(\frac{Btu}{hr}\right)$

$Q_{WallMiddle} =$ Rate of heat loss through middle section of Basement Wall $\left(\frac{Btu}{hr}\right)$

$Q_{WallLower} =$ Rate of heat loss through lower section of Basement Wall $\left(\frac{Btu}{hr}\right)$

$Q_{BasementWall} =$ Sum of rate of heat loss in Basement Wall $\left(\frac{Btu}{hr}\right)$

$Q_{SL} =$ Rate of heat loss through service load $\left(\frac{Btu}{hr}\right)$

$Q_{Total} =$ Total field loads $\left(\frac{Btu}{hr}\right)$

$R_{effective} =$ Effective R-value of upper, middle, or lower basement wall section $\left({}^\circ F - ft^2 - \frac{hr}{Btu}\right)$

$R_{wall} =$ R-value of wall $\left({}^\circ F - ft^2 - \frac{hr}{Btu}\right)$

$R_{insulation} =$ R-value of insulation $\left({}^\circ F - ft^2 - \frac{hr}{Btu}\right)$

T_{inital} = Initial temperature of produce $(°F)$

T_{final} = Desired final temperature of produce $(°F)$

ΔT = Change in temperature $(°F)$

wt = Weight of produce $(lbs.)$

Introduction

Local food systems can contribute to socially, economically, and ecologically beneficial food production for local communities. In order to deliver quality produce to the consumer, local food systems must utilize rapid cooling and cold storage technology. In the past thirty years, the number of local farms increased 11.2% thus the need for energy efficient cold storage units (USDA, 2013). Cold storage is essential for vegetable farmers to preserve produce quality and extend the revenue period. The Student Organic Farm (SOF) asked the Local Roots team to design a low cost cold storage unit.

Cold storage is a critical component in the food supply chain. Without rapid cooling and appropriate storage conditions, produce deteriorates rapidly. Nutritional losses and even spoilage of entire crops can occur. Initial rapid cooling to extract latent field heat extends shelf life and maintains quality produce.

The idea of using underground cold storage is nothing new; in fact it has been used for thousands of years. Native Americans began using underground storage for large amounts of yams as long as 40,000 years ago (Gush, 2013). As the industrial age enabled the discovery of cheap electricity, the refrigeration cycle and the manipulation of thermodynamics, cold cellars were replaced with the industrial refrigeration units found at most commercial food processing plants, restaurants, or household kitchens. Currently, cold storage units are experiencing a 'rediscovery' period due to their ability to ensure a year round supply of local produce at a very low energy cost.

Cold storage units are above ground, in an insulated basement or in buried containers. A basis for underground cold storage is the constant temperature of the soil approximately 5 feet below grade. Soil acts as insulation against wind and ambient conditions. Although soil temperature values vary by region, this constant temperature helps regulate storage conditions year round, preventing winter freezing and summer spoilage.

Modern cold storage units control the temperature and humidity using a variety of technologies. CoolBot controllers and evaporative cooling are popular methods among small-scale farmers to maintain storage at low costs. The CoolBot works by manipulating an AC unit to act as a compressor, enabling the AC to achieve much lower temperatures then intended. Evaporative cooling works by running warmer air through a cooler water pad that then takes the heat out of the air, essentially working like sweat in the human body. Using the constant soil temperature with modern insulation materials, efficient refrigeration technology and renewable energy, farmers can have affordable and sustainable food storage systems.

SOF currently uses an above ground commercial refrigeration system. Professor John Biernbaum, the client, has asked the group to design a cold storage unit to be placed in a basement. The unit must store a range of produce from the fall and summer seasons.

Problem Statement

To provide a diversity of vegetables over a long season, small-scale vegetable producers need to use energy efficient cold storage methods to reduce costs and extend the revenue period while maintaining produce quality and freshness. The Student Organic Farm currently uses 95% of its electricity for refrigeration. Our problem statement is to design an efficient cold storage unit using as much natural cooling and ventilation as possible that will store the range and quantity of the SOF's produce and reduce the current electricity cost by 70%.

Justification

Energy efficient cold storage is an essential element to a sustainably designed local food system. Cold storage allows local farmers to provide seasonal nutrition to the community year round at a low cost. Local farmers need to find ways to increase profitability while adhering to sustainability principles. The optimal cold storage solution will allow farmers to store and sell their products year round, with minimal energy use.

Major changes in the food system are necessary on the local level when the average plate of food has travelled 1,500 miles (Pirog, 2011). A question can then be asked; can efficiently designed local food systems benefit the environment, farmers and the local community?

Local food systems can be designed in a way that reduces transportation costs, a study done in the United Kingdom found that if the external cost of agriculture up to the farm gate where switched to organic local production, $1.55 billon could be saved per year due to production and transportation (Pretty, 2005). Most importantly, local food systems, by not relying on global infrastructure, may be able to create a self-sustaining food system that is resilient to a larger economy downturn. Due to the fact that this system does not rely on a mass transport system or copious amounts of oil, local farmers can be prepared to keep themselves afloat during tough times. However, whether these benefits are actualized is dependent upon the design of each local system.

Local food systems have been shown to increase the economic and social interaction of the community through various farmers markets or Community Supported Agriculture (CSA) programs. This establishes a human connection and enables communication between the food producer and consumer. Farmer's markets and C.S.A. programs help re-circulate money through the local economy.

Farmers produce seasonally nutritious and flavorful products (Wixson, 2008). Local produce is harvested at peak season, when it has the most nutrients and flavor (Klavinski, 2013). However, this is not the case in large box grocery stores where the produce is picked early to ripen unnaturally using ethylene during transport (Postharvest, 2014). This leads to deterioration and nutrient loss in the produce (USA, 2012).

Regardless of the benefits of organic, non-GMO and local foods, there is a growing market of consumers demanding these products (Jazar, 2009). By building a cold storage unit, the organic farm will be able to reach out to a niche of consumers willing to pay extra for high end produce, year round (Shapley, 2006). For example, the University of Minnesota built a root cellar in 2001 to serve a farm similar in size to the SOF. The gross income of the farm increased by $10,000 in CSA sales and by $2,400 in extended season sales to the Whole Foods Co-Op (U of M, 2014).

Based on MSU estimates, the current cold storage refrigeration accounts for over 95% of the energy used on the SOF (Walton, 2008). A MSU horticulture student calculated that without the use of a cold cellar it would take over 3,200 hardwood trees to sequester the carbon generated from the current refrigeration system's energy needs (Walton, 2008). This is the major obstacle preventing the SOF from becoming carbon neutral. Building an energy efficient cold cellar would greatly reduce this energy cost, while enabling the SOF to generate revenue from quality produce throughout the winter.

The SOF owns 15 acres of land, but is only using 3-5 acres at a time due to crop rotation. According to the USDA in 2013, there were 265,000 other farms in the United States between 1-

9 acres. Additionally, this size category of farms has seen an 11.2% increase from 1982-2011. This indicates that an energy efficient cold storage unit similar to the one designed for the SOF is applicable nationwide (USDA, 2013).

The SOF prides itself on its sustainable farming practices. The basement cold storage unit will further that sustainability model by allowing the farm to store produce year round at a fraction of the energy usage. The savings the farm will generate will enable them to further improve their model of sustainable farming and provide benefits to the community. Furthermore, the addition of a cold storage unit will complete the missing link in a sustainable local food supply chain.

Background

Michigan State University's SOF has raised funds to construct a pole barn with a basement. Dr. John Biernbaum has asked the Local Roots team to design an energy efficient cold storage unit to occupy a corner of the basement. Designing the basement is outside the scope of the Local Roots team. The on farm location of the basement is outlined in Figure 1. Note the adjacent woodlot and greenhouses, they can provide shade to help cool the entrance to the cellar. Dr. Biernbaum hopes the unit will reduce farm costs while helping the farm become more carbon neutral. A major obstacle to this goal is the electricity currently used in refrigeration, comprising over 95% of the farms demand. The main goal of the cold storage unit is to reduce the electricity currently used for refrigeration by 70%.

Figure 1: Potential Cold Storage Site

Michigan State University's SOF was founded by a group of students in 1999. The SOF is now a certified organic 15-acre teaching and production farm ran by Dr. John Biernbaum, students and volunteers. Operating year round, the farm uses seven passive solar greenhouses, maintaining a temperature where vegetables including spinach, kale, collards, chard, cabbage, cilantro, parsley, radishes, and beets grow during the winter. The farm also grows, sells, and stores produce such as squash, garlic, potatoes, onions, cabbage, rutabaga, and carrots.

To generate revenue, the SOF sells their produce through Community Supported Agriculture (CSA), MSU resident's halls, and/or an on campus farm stand. Michigan residents who are members of the CSA receive fresh produce 48 weeks of the year. Quantity of produce sold is dependent on the season.

For the produce to remain fresh, both temperature and humidity must be maintained through their storage life. Produce is kept either in a cool and dry room at 50-60 F/60-70% relative humidity or a cold and damp room at 36-40 F/ 85-95% relative humidity. The SOF is able to maintain these conditions with two industrial sized cooling units to ensure proper temperature and use either humidifiers or dehumidifiers to maintain proper humidity.

To store produce, the farm uses a variety of containers, including bulk bins, totes and crates. Dr. John Biernbaum plans to keep using the same containers, but in a drastically different storage space. The task he assigned is to design an energy efficient cold storage unit that can accommodate the current harvest and storage conditions. Although the client originally planned to build a basement beneath the pole barn, his plans may change after analyzing the costs and benefits of basement storage. Specifically, the client is interested in whether the cost of excavating and pouring concrete justifies the added insulation gain of the soil. The Local Roots team has been asked to design a basement cold storage unit and an above ground unit, to compare the construction costs and insulative savings.

The client is interested in the comparison between above and below ground to see if it is really worth it to build a basement structure. With modern insulations and efficient cooling technology, the above ground cellar may be a better option. The client also was interested in a comparison between using laid blocks or poured concrete for construction.

Objectives

The purpose of the project is to design a cold storage unit that greatly reduces electricity use. To that end, the will accomplish the following objectives:

1. To design a cool and cold storage unit for the SOF that will store 32,250 lbs of maximum produce load at optimum temperature and humidity ranges
2. To design a cool and cold storage unit capable of completely removing field heat within 24 hours
3. To design ventilation and refrigeration system specifications for the SOF cool and cold storage units to reduce electricity cost by 70%
4. To optimize cool and cold storage unit dimensions and unit operations to adjust to SOF's produce seasonality needs and minimize energy footprints by April 25, 2014

The unit will be designed to maintain conditions during temperature extremes and maximum produce loads. Objectives relating to produce quality cannot be evaluated and are omitted.

Constraints

Project constraints are listed below. It is desired that cold cellar function in the basement for new pole barn to be constructed at the site in the next few years. However, the design team will compare that cost and energy requirements to that of an above ground storage option

- 70% reduction in electricity use
- 90% of high temperature extremes can be handled by the unit
- <4 year payback period
- 32,250 lbs of produce can be stored maximum storage weight
- 120,000 ft^3 of produce maximum storage volume
- 27 in. x 48 in. motorized pallet jack with a 180° turning radius must be able to navigate the cellars
- 50-60 F and 60-70% relative humidity for the cool and dry chamber (Biernbaum, 2009)
- 36-40 F and 85-95% relative humidity for the cold and damp chamber (Biernbaum, 2009)
- < 24 hours field heat removal
- Compatible with proposed SOF pole barn basement

Deliverables

The deliverables represent the phases of information gathering and analysis necessary to complete the project.

- Comprehensive design plan that stores 32,250 lbs of produce and removes field heat within 24 hours
- Optimized energy, room utilization and storage configuration plan that reduces the SOF electricity use by 70%
- Comparative analysis between below and above ground construction including construction and concrete options

Background Calculations

Containers

To design an easily accessible layout for the room, the maximum quantity of storage containers was determined. The client provided the maximum pounds of produce in addition to the size of the storage containers, which include a 55-gallon bulk bin, an 18-gallon tote and a 6.3-gallon bulb crate. The bulk bins, crates and totes are pictured in Figure 2. The client provided estimates for the weight of each produce type that could fit in each container. These estimates were used to calculate the total number of containers required. These calculations are shown in Tables 1 and 2.

Table 1: Summer produce load and total containers

Produce	**Cold or Cool**	**Weight of Produce**	**Volume of Container**	**Weight per container**	**Number of Containers**	**Volume of Containers**
		lbs	*ft^3*	*lbs/container*	*Containers*	*ft^3*
Tomatoes	Cool	1,050	0.84	30	35	29.41
Eggplant	Cool	100	2.41	50	2	4.81
Peppers	Cool	350	2.41	50	7	16.84
Cucumber	Cool	300	0.84	30	10	8.40
Lettuce Head	Cold	60	2.41	15	4	9.63
Leafy Greens	Cold	40	2.41	10	4	9.63

Table 2: Fall produces load and total containers

Produce	Cold or Cool	Weight of Produce	Volume of Container	Weight per container	Number of Containers	Volume of Containers
		lbs	*ft^3*	*lbs/container*	*Containers*	*ft^3*
Beets	Cold	3,500	2.41	70	50	120.31
Cabbage	Cold	4,500	7.35	750	6	44.11
Carrots	Cold	6,000	2.41	70	86	206.94
Celeriac	Cold	1,000	2.41	65	16	38.50
Garlic	Cold	750	2.41	18	42	35.29
Onions	Cold	3,000	0.84	28	108	90.75
Rutabagas	Cold	1,500	2.41	70	22	53.94
Potatoes	Cold	7,000	0.84	30	234	196.63
Winter Squash	Cool	5,000	0.84	32	157	131.92

Figure 2: 55-gallon bulk bin (Willow, n.d.), 18-gallon tote (Sterilite, n.d.), and 6.3-gallon bulb crate (Vented, n.d.)

Design of the Cold and Cool Rooms

The cold storage unit planned at the SOF will be a basement construction with a vestibule entrance. Adjacent to the vestibule is the washroom where the produce will enter the facility and be washed before being moved by a motorized pallet jack to the cold rooms on the opposite side of the vestibule. The vestibule is necessary to minimize conduction through the interior wall, by creating an additional barrier between the outdoor entrance and the cold storage rooms. There will be a spiral staircase from the washing room to the pole barn to minimize space use. By adding the staircase SOF workers can access the basement through the pole barn, and the second exit door is necessary to meet fire code. (Handbook 66, n.d.)

The client's original food storage estimations are 40 ft by 22 ft by 8 ft. Container calculations will be used to verify this estimate and for optimization. The proposed layout is depicted in Figure 3. The client has stated that the pole barn will be larger than the cold storage portion of the basement.

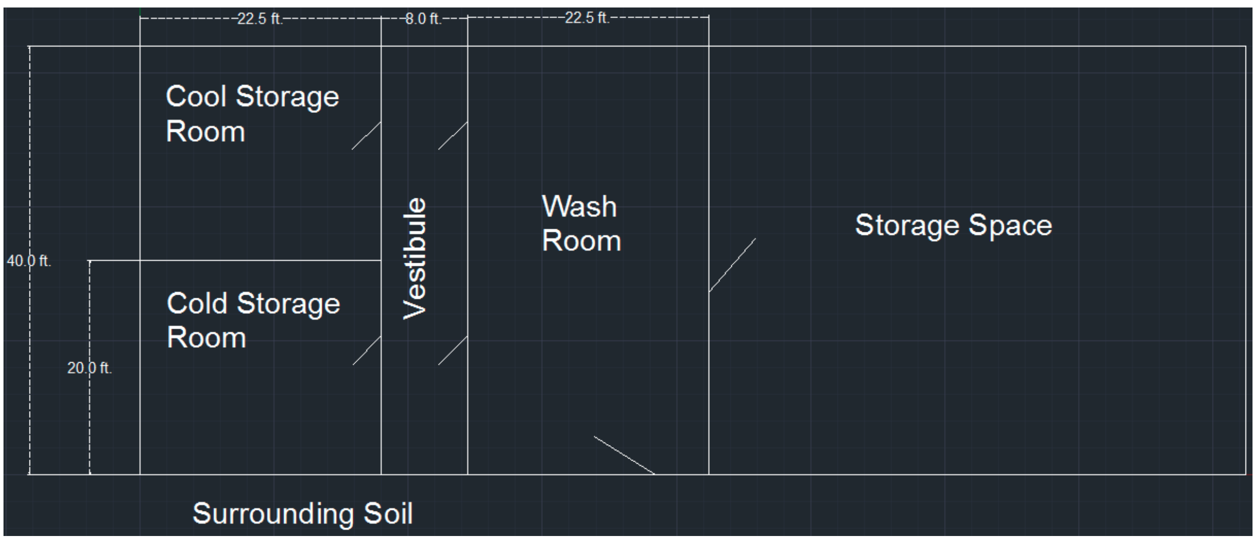

Figure 3: Preliminary Plan View of Proposed Structure

Based on the calculations shown in Table 1 and 2, the maximum produce load during the fall is depicted in Table 3.

Table 3: Produce container breakdown

Bin	Cold Room	Cool Room
55-gallon bulk bins	6	0
18-gallon totes	216	0
6.3 gallon bulb crates	342	157

Fall produce represents the maximum cellar load. Room size must accommodate the full mobility use of a motorized pallet jack. T Pallet jack dimensions are 27’’ x 48’’ with a turning radius of 180°. To ensure proper air circulation and vertical space utilization, crates will be stacked on three layers of shelving.

The client’s initial estimates of two 20 ft x 22 ft rooms will not accommodate all fall produce and allow pallet jack access. As show in Figure 4 room sizes needed to be increased to 32 ft x 22 ft.

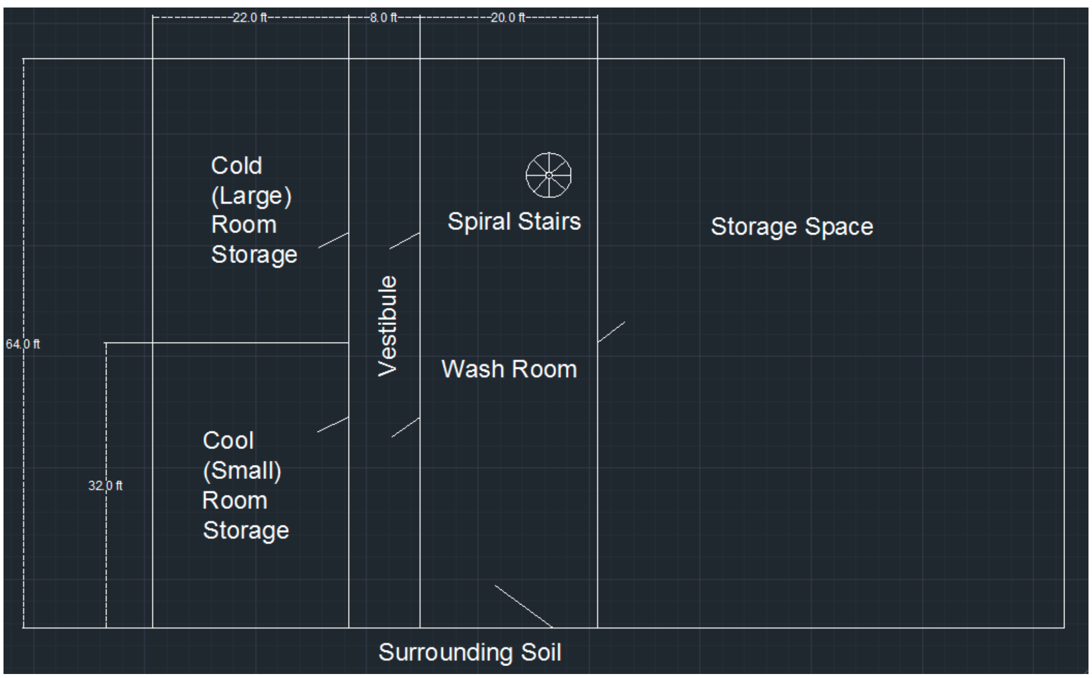

Figure 4: Plan view of the basement

Figures 5 and 6 depict the room layout with each red circle represents one 55-gallon bulk bin. The mustard colored rectangles represent the 18-gallon totes. In the cool room totes are stacked four high, and in the cold room they are stacked four and five high depending on their location in the room. Two inch spacing stacks ensures proper air circulation (Saltveit, 2013). The brown rectangles represent the shelving units for the 6.3-gallon bulb crates. Each rectangle represents nine bulb crates, with three stacked per shelf. Two inch spacing between the stacked bulb crates ensures proper airflow. Container arrangement, spacing and numbers are used to determine the necessary room dimensions.

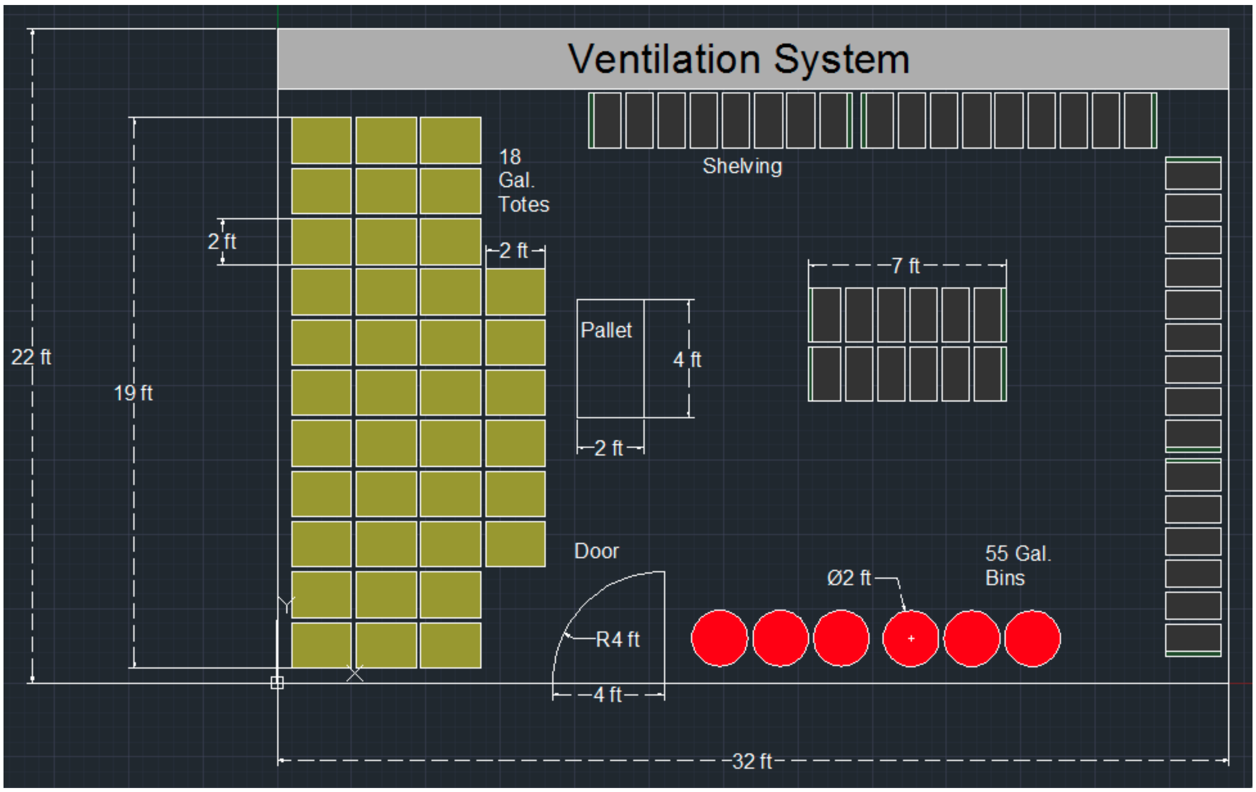

Figure 5: Plan view cold room

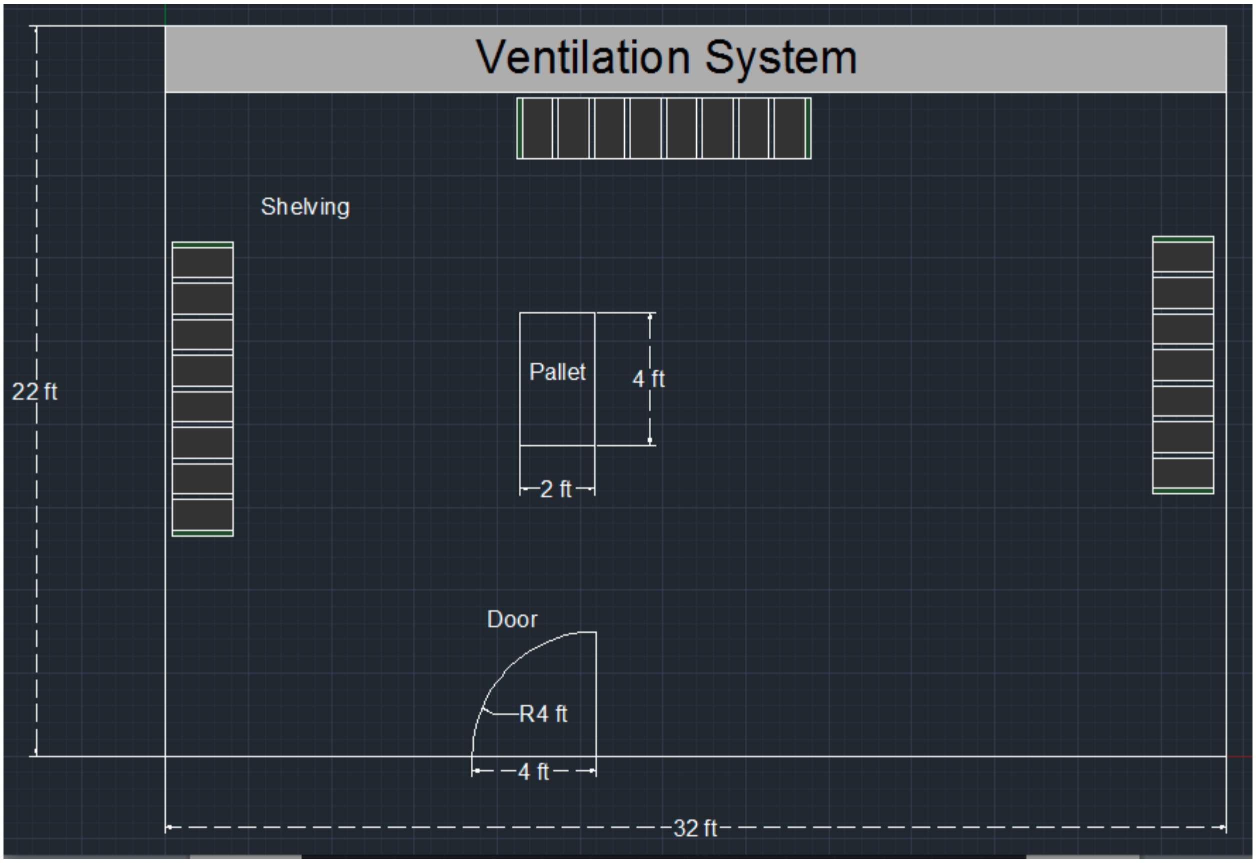

Figure 6: Plan view cool room

Heat Load

A cold storage unit needs to maintain a specific range of temperature and relative humidity to ensure quality produce. These conditions are 50-60 ºF with 60-70% RH for the cold room and 36-40 ºF with 85-95% RH in the cool room. To design a refrigeration system, the maximum heat load must be calculated. Heat load is calculated using the amount of heat removal required in BTU/hr from the room to maintain conditions. Maximum heat load of produce occurs from latent field heat within 24 hours of harvest and loaded into the room.

Four major sources of heat contribute to the heat load, or the total amount of heat the refrigeration system must remove (Boyette, 1991). Heat enters the storage via: 1) conduction through the walls, 2) respiration from the vegetables, 3) latent field heat from warm vegetables and 4) service load generated from lights, fans and people coming in and out of the unit. These total heat sources will be used to determine the peak refrigeration capacity (Boyette, 1991).

Conduction through Walls

Conduction through the walls, floor and ceiling is a constant source of heat gain or loss. Heat gain is not the same for all surfaces of the room due to differences in insulation, unequal areas of the wall and differences in temperature gradient. R-values of the building material are needed to calculate heat conduction. Three distinct formulas are used to determine the heat flux of basement walls depending on the depth of the wall below grade (ground level). Different equations are used for the upper section, the middle section and the lower section of the wall. Equations differ depending on the depth of the wall below grade as added soil increases thermal resistances between the wall and the outside air, resulting in a decreased heat flux (Siegenthaler, 2011).

The upper section is the area that extends from the exposed area above ground to a depth of 2 feet below grade. Equations 1 and 2 are used to calculate the heat flux of the upper section of the basement wall

$$R_{effective} = R_{BasementWall} + R_{insulation} \tag{Eq.1}$$

$R_{effective}$ = *Effective R-Value of wall* $\left(\frac{F \times ft^2 \times hr}{BTU}\right)$

$R_{insulation}$ = *R-Value of wall insulation* $\left(\frac{F \times ft^2 \times hr}{BTU}\right)$

$$Q_{WallUpper} = \frac{A \times \Delta T}{R_{effec}} \qquad \text{(Eq. 2)}$$

$Q_{WallUpper}$ = *Rate of heat loss through the upper wall* $\left(\frac{BTU}{hr}\right)$

A = *floor area* (ft^2)

ΔT = *Basement air temperature - outside air temperature* (F)

The middle section includes the wall area from 2 to 5 feet below grade. Equations 3 and 4 are used to calculate the heat flux of the middle section of the basement wall. The values in Equation 3, 5, and 8 came from a textbook (Siegenthaler, 2011) and account for the insulation values of the soil.

$$R_{effective} = 7.9 + 1.13 R_{insulation} \qquad \text{(Eq.3)}$$

$$Q_{WallMiddle} = \frac{A \times \Delta T}{R_{effec}} \quad \text{(Eq. 4)}$$

$Q_{WallMiddle} = \textit{Rate of heat loss through the middle wall} \left(\frac{BTU}{hr}\right)$

The lower section includes the wall area more than 5 feet below grade. Equations 5 and 6 are used to calculate the heat flux of the bottom section of the basement wall.

$$R_{effective} = 11.3 + 1.13R_{insulation} \quad \text{(Eq.5)}$$

$$Q_{WallLower} = \frac{A \times \Delta T}{R_{effec}} \quad \text{(Eq. 6)}$$

$Q_{WallLowerr} = \textit{Rate of heat loss through the lower wall} \left(\frac{BTU}{hr}\right)$

To calculate the total heat flux of the basement wall Equation 7 is used.

$$Q_{BasementWall} = Q_{WallUpper} + Q_{WallMiddle} + Q_{WallLower} \quad \text{(Eq. 7)}$$

$Q_{Basement\ Wall} = \textit{Rate of heat loss through the basement wall} \left(\frac{BTU}{hr}\right)$

To calculate the heat flux from the basement floor Equation 8 is used.

$$Q_{Floor} = 0.024 A \times \Delta T \quad \text{(Eq.8)}$$

$Q_{Floor} =$ *Rate of heat loss through the floor* $\left(\frac{BTU}{hr}\right)$

To calculate the heat flux of the ceiling Equations 9 and 10 are used.

$$R_{effective} = R_{ceiling} + R_{insulation} \quad \text{(Eq.9)}$$

$R_{Ceiling} =$ *R-Value of ceiling* $\left(\frac{F \times ft^2 \times hr}{BTU}\right)$

$$Q_{Ceiling} = \frac{A \times \Delta T}{R_{effec}} \quad \text{(Eq.10)}$$

$Q_{Ceiling} =$ *Rate of heat loss through the ceiling* $\left(\frac{BTU}{hr}\right)$

To calculate the heat flux of the interior walls that separate the cleaning area from the cellar Equations 11 and 12 are used.

$$R_{effective} = R_{InteriorWall} + R_{insulation} \qquad \text{(Eq.11)}$$

$$R_{InteriorWall} = \text{R-Value of Interior Wall} \left(\frac{F \times ft^2 \times hr}{BTU}\right)$$

$$Q_{InteriorWall} = \frac{A \times \Delta T}{R_{effective}} \qquad \text{(Eq.12)}$$

$$Q_{InteriorWall} = \text{Rate of heat loss through the Interior Wall} \left(\frac{BTU}{hr}\right)$$

To calculate the total heat flux of the basement Equation 13 is used.

$$Q_{HL} = Q_{BasementWall} + Q_{InteriorWall} + Q_{Floor} + Q_{Ceiling} \qquad \text{(Eq.13)}$$

$$Q_{HL} = \text{Total rate of heat loss through basement} \left(\frac{BTU}{hr}\right)$$

Equations 1-13 can be found using source (Siegenthaler, 2011).

Heat of Respiration

Plant respiration produces heat as a by-product. Produce is still a living product while in storage and thus generates heat through cellular respiration. The level of respiration for each vegetable is calculated by measuring the level of CO_2 production from respiration. Cellular respiration generates 2.55 calories of vital heat for every 1 mg of carbon dioxide produced×

(Handbook 66, n.d.). Heat of respiration for each vegetable was calculated by measuring how much CO_2 was produced in a day and converting that to calories. The heat of respiration for a vegetable at 50 F is approximately 19 times higher than after cooling. That means the vegetables in the cold room will generate much less heat due to respiration than the cool room. To calculate the heat of respiration for a particular produce Equation 14 is used.

$$Q_{HR} = wt. \times HR_{coefficient} \tag{Eq. 14}$$

$$Q_{HR} = \textit{Rate of heat loss through heat or respiration} \left(\frac{BTU}{hr}\right)$$

Field Heat

The majority of heat is introduced when warm produce from the field is initially brought into a cool space. The latent heat energy contained in the vegetables is called field heat. When fresh vegetables are harvested from the field they are cut off from their only source of water and nutrition. This causes rapid deterioration, as they lose weight, flavor, nutritive value and overall appeal. Cooling the produce significantly slows down this rate of deterioration, greatly increasing the storage life (Wilhoit, 2009). The most critical role of cold storage units is removing the field heat quickly before the produce deteriorates. To maintain quality produce, the recommended range of removal time is 12-36 hours (Handbook 66, n.d.). The calculations add a constraint that the field heat must be removed within 24 hours. To calculate field heat the mass of produce, the specific heat above 32 F and the temperature difference between the initial produce temperature and the temperature of the cellar where the produce will be stored is needed. Equation 15 is used to calculate field heat. The field heat is removed when the produce is the same temperature as the room.

(Eq. 15)

$$Q_{HF} = wt. \times SH \times \Delta T$$

$Q_{HF} =$ *Rate of heat loss through field heat* $\left(\frac{BTU}{hr}\right)$

$$SH = Specific\ heat\ coefficent\ for\ produce\ \left(\frac{BTU}{hr}\right)$$

Service Load

The final source of heat is the service load and is due to operational factors such as doors opening/closing, lights, fans, and people working in the cellar. Due to the level of difficulty involved in calculating these heat sources, the service load is estimated as ten percent of the other heat sources (Handbook 66 n.d.). These values are not constant and difficult to calculate so Equation 16 is used.

$$Q_{SL} = 0.1\,(Q_{HL} + Q_{HR} + Q_{HF}) \quad \text{(Eq.16)}$$

$Q_{SL} = Rate\ of\ heat\ loss\ through\ service\ load\ \left(\frac{BTU}{hr}\right)$

$Q_{HL} = Rate\ of\ heat\ loss\ through\ heat\ load\ \left(\frac{BTU}{hr}\right)$

$Q_{HR} = Rate\ of\ heat\ loss\ through\ heat\ of\ respriation\ \left(\frac{BTU}{hr}\right)$

$Q_{HF} = Rate\ of\ heat\ loss\ through\ feild\ heat\ \left(\frac{BTU}{hr}\right)$

Total Heat Load

Finally, the sum of the conduction though the walls, heat of respiration, field heat, and service load can be summed up by Equation 17 to get the total heat load.

$$Q = Q + Q + Q + Q \qquad \text{(Eq.17)}$$

$Q_{Total} = Total\ rate\ of\ heat\ loss\ throughout\ the\ basement\ \left(\frac{BTU}{hr}\right)$

Equations 14-17 can be found in the reference (Boyette, 1991) and (Handbook 66, n.d.).

Maximum Heat Load

Q_{total} is the maximum heat load, or the maximum amount of heat necessary to remove from the system to maintain optimal storage conditions. Q_{total} decreases significantly once the field heat is removed, as the respiration of the produce slows down. Maximum heat load is calculated as BTU/hr. One ton of refrigeration is equivalent to 12,000 BTU/hr. The Seasonal Energy Efficiency Rating of the air conditioning unit is used to determine energy consumed per cooling delivered.

Background Calculations

To optimize the system, the effect of various components on the heat load must be analyzed. To analyze the heat load, initial estimates for room dimensions and insulation materials are made. These estimates are used as placeholders to calculate the maximum refrigeration needed to cool the produce within a 24-hour period, using the equations outlined above. The dimensions used for both rooms are 32 ft x 22ft x 8ft, as calculated above.

Several parameters cannot be optimized. These include the produce load, the outside temperature, and the temperature of the rooms and the relative humidity of the rooms. Therefore, the insulation used and the dimensions of the room represent the variables that can be optimized. The refrigeration and ventilation systems will be designed to accommodate these optimized parameters.

The outside temperature is critical when considering conduction through the wall. The greater the temperature difference between the inside and outside results in a larger heat gain through the structure. The SOF will be moving the bulk of fall produce into the cellar in August, so the August temperature will be used to calculate maximum conduction load. In order to design for temperature extremes, the 90^{th} percentile of high temperatures for August was used (Marks, 2014). The daily high temperatures in August for the past five years were collected from the MSU Enviro-Weather station located at the MSU Horticultural Farm. The data was then arranged from low to high with the 90^{th} percentile being used as the high temperature for August which is 89.5 °F.

The other two set parameters, temperature and relative humidity ranges are inherent to the requirements of the produce and need to be maintained throughout the season to prevent possible spoilage. The cold room will have a range of temperatures between 36-40 F and a relative humidity between 85-90%. The cool room will operate between 50-60 F and a relative humidity between 60-70%.

There are two placeholders that can be used for later optimization including: dimensions of the room, and the R-value of insulation. Based on the produce load provided by Dr. Biernbaum the initial estimates for each of the rooms will be 32 ft x 22 ft. x 8 ft. By decreasing the room's dimensions, the heat conduction through the walls will be reduced because the area will shrink. Room volume of the room will also be reduced, resulting in less air that needs to be cooled. Although the initial design has two equally sized rooms, partitioning the rooms or decreasing the dimensions can be optimized.

To accurately model the cooling power required to remove field heat, the field temperature must be known. Due to differences between root and field vegetables, as well as unique harvest schedules, each produce will be brought in at varying temperatures. To calculate these temperatures, data from the MSU Enviro-Weather station located at the MSU horticulture farm was used. All vegetables were assumed to be in steady state with the air or soil. Table 4, shows the initial temperature of produce entering the cellar, along with the month of harvest.

Table 4: Initial temperature for produce and harvest month (Enviro-Weather, 2014)

Produce	**Cold or Cool**	**Harvest Month**	**Root or non-root vegetable**	**Harvest Temperature (°F)**
Beets	Cold	August	Root	74.1
Cabbage	Cold	August	Non-root	89.5
Carrots	Cold	November	Root	49.1
Celeriac	Cold	October	Root	69.9
Garlic	Cold	August	Root	74.1
Onions	Cold	August	Root	74.1
Potatoes	Cold	October	Root	69.9
Rutabagas	Cold	August	Root	74.1
Winter Squash	Cool	August	Non-root	89.5

The initial R-value will also be a placeholder for the original calculations. The placeholder R-value that will be used is an industrial standard of 28 (ASHRAE, n.d). The industrial standard R-value consists of 4 inches of polystyrene in addition to supplemental insulation to achieve an R-value of at least 28. Polystyrene is recommended as a vapor barrier along the outside of the unit in several cold storage design articles because of its ability to retain heat and handle moisture (Wilhoit, 2009). The additional insulation selected will be placed on the interior of the unit and must be a material that can be washed. Additionally, 1 inch blue board will be used to insulate the floor. The R-value can be optimized by comparing the cost required for construction materials to the savings on refrigeration costs with a reduced heat load.

With these placeholders the original estimate of the refrigeration load needed to cool the produce within a 24 hour period was calculated in the following section.

Conduction through Walls Calculation

As shown in Figure 7 the cold storage basement unit has two exterior basement walls and two interior walls in both the cold and cool rooms, with one interior wall shared between the rooms. The maximum heat gained through conduction can be calculated for the basement walls, interior walls, floor and ceiling using the required room temperature, an outside temperature of 89.5 F and an R-value of 28 for all walls, floor and ceiling.

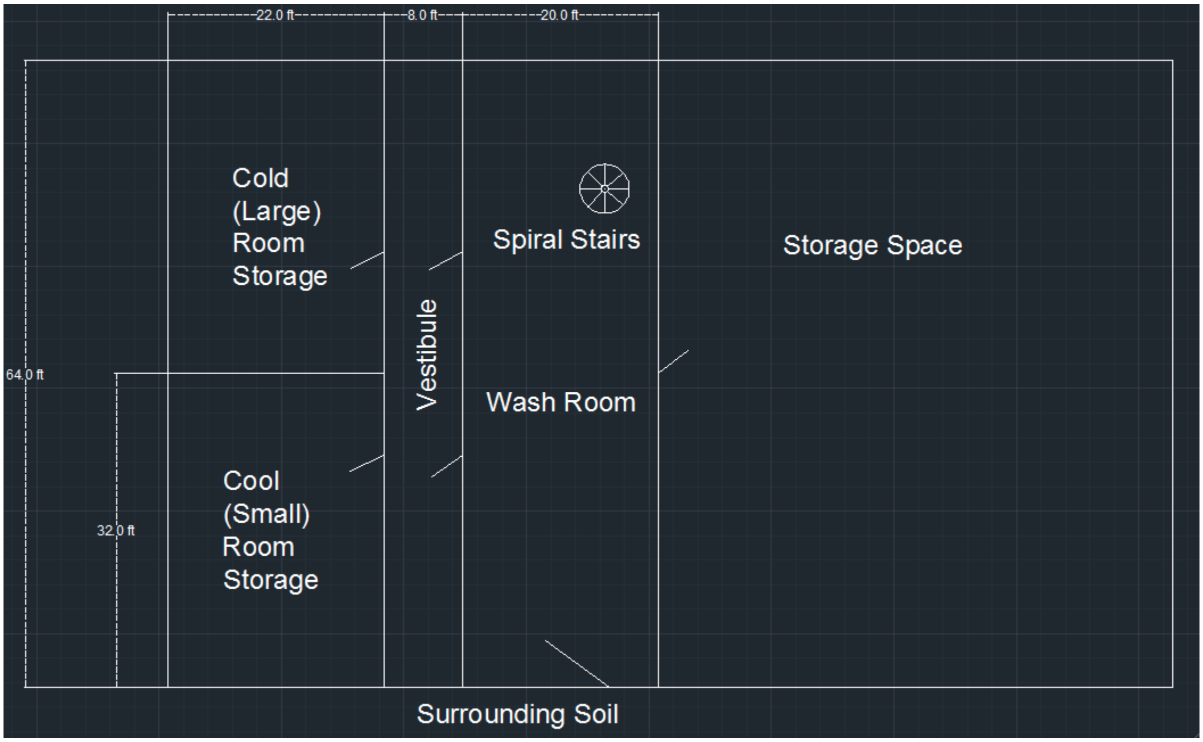

Figure 7: Plan View Cold Storage Basement

The heat flux through the basement walls can be calculated using Equation 7. Both the cold and cool rooms have two basement walls with dimensions of 32 ft. x 8 ft. and 22 ft. x 8 ft. It was calculated that the heat flux through the basement walls in the cold room is 582 BTU/hr and the heat flux thru the basement walls in the cool room is 465 BTU/hr.

The interior wall that separates the vestibule from the storage room can be calculated by using Equation 12. The dimensions for the interior wall are the same for the cold room and cool rooms at 32 ft. x 8 ft. For calculations, it was assumed that the vestibule temperature is 60Fin August. This assumption is made because it will be cooler than the outside air, but warmer than the food storage rooms. The maximum heat flux through the interior wall of the cold room was calculated to be 183 BTU/hr. The maximum heat flux through the cool interior wall was calculated to be 92 BTU/hr.

The heat flux through the basement floors of both the cold and cool rooms can be calculated by using Equation 8. With the dimensions of both the cold and cool room's floors at 32 ft. x 22 ft., the maximum heat flux through the basement floor of the cold room and cool rooms were calculated to be 837 BTU/hr and 668 BTU/hr, respectively.

The heat flux through the ceiling was calculated using Equation 10. Again, assuming the maximum possible heat load, the temperature of the pole barn above was assumed to be 89.5 °F. With the dimensions of the ceiling at 32 ft. x 22 ft., the heat flux of the ceiling in the cold and cool rooms was calculated to be 1,245 BTU/hr and 994 BTU/hr, respectively.

Finally, the interior wall that separates the cold room from the cool room was calculated using Equation 12. With the gradient moving from warmer air to colder air, the cool room will lose heat while the cold room will gain the heat lost from the cool room. With the dimension of the interior wall at 22 ft. x 8 ft., the heat loss of the cool room is 32 BTU/hr and the heat gain of the cold room is 32 BTU/hr.

The total heat flux for both the cold and cool rooms was calculated using Equation 13. The total heat flux of the cold room was calculated to be 2,878 BTU/hr. The total heat flux in the cool room was calculated to be 2,186 BTU/hr.

Heat of Respiration Calculations

To calculate the heat of respiration, the mass of produce is needed in addition to the heat of respiration coefficient. Equation 14 was used to calculate the heat of respiration of each product. Table 5 shows the quantity of produce, heat of respiration coefficient and the heat of respiration given off each product.

Table 5: Heat of respiration for given produce

Product	Quantity	Respiration Cold	Respiration Cool	Heat of Respiration
	lbs	*BTU/lb/hr*	*BTU/lb/hr*	*BTU/hr*
Beets	3,500	0.05	-	160.42
Cabbage	4,500	0.03	-	123.75
Carrots	6,000	0.09	-	550.00
Celeriac	1,000	0.04	-	36.67
Garlic	750	0.06	-	41.25
Onions	3,000	0.01	-	41.25
Potatoes	7,000	0.09	-	630.00
Rutabagas	1,500	0.03	-	41.25
Winter Squash	5,000	-	0.11	566.04
Total Cold	27,250			1584
Total Cool	5,000			567

The total heat of respiration for the cold room is 1584 BTU/hr heat gain. The total heat of respiration for the cool room is 567 BTU/hr heat gain. The cool room has a greater heat of respiration gain than the cold room, even though the cold room has more produce, because at higher temperatures produce have a higher metabolic rate, resulting in the heat of respiration coefficient being larger. Although several physical characteristics determine the respiration rate of produce, the most important factor is the temperature of the produce. A sample calculation for beet's heat of respiration can be found in Appendix A.

Field Heat Calculations

With the initial temperature of the produce shown in Table 6, the desired temperature of the cold and cool rooms at 40 F and 50 °F, and the difference in temperatures also shown in Table 5, Equation 15 was then used to determine the field heat for each produce. Table 6 shows the pounds of produce, storage temperature, field temperature, specific heat above 32 °F, and the field heat for each product.

Table 6: Field heat for each produce

Product	Quantity	Storage Temp	Field Temp	ΔTemp	Specific Heat	Field Heat
	lbs	*℉*	*℉*	*℉*	*BTU/lb/℉*	*BTU*
Beets	3,500	40	74.1	34.1	0.9	107,415
Cabbage	4,500	40	89.5	49.5	0.94	209,385
Carrots	6,000	40	49.1	9.1	0.9	49,140
Celeriac	1,000	40	69.9	29.9	0.91	27,209
Garlic	750	40	74.1	34.1	0.69	17,647
Onions	3,000	40	74.1	34.1	0.9	92,070
Potatoes	7,000	40	69.9	29.9	0.82	171,626
Rutabagas	1,500	40	74.1	34.1	0.91	46,547
Winter Squash	5,000	50	89.5	39.5	0.88	173,800

A sample field heat calculation for beets can be found in Appendix A.

To size the refrigeration system the maximum heat load must be known. The maximum heat load is always when the most produce is introduced to the cellar. August is the month with the most produce. Beets, cabbage, garlic, onions, and rutabagas are harvested and stored in the cold room. Winter squash is stored in the cool room. Therefore the BTU/hr needed to cool the produce within 24 hours is used to size the refrigeration system. The refrigeration system designed for August will be sufficient to handle other months, as the field heat introduced to the system is much lower.

Table 7 shows the total field heat and the removal rate required to cool the produce in 24 hours. The calculations are only for the month of August. Carrots, celeriac, and potatoes are excluded.

Table 7: Total field heat and removal rate

	Total Field Heat	Field heat removal rate
	BTU	*BTU/hr*
Cold Room	473,064	19,711
Cool Room	173,800	7,242

Service Load Final Calculations

The service load with the given maximum produce load, a field temperature of 89.5 F and the desired temperature of the cold and cool rooms to be 40 F and 50 F respectively, the service load of the cold room is 2,302 BTU/hr and the cool room is 2,186 BTU/hr.

A final breakdown of the various heat flows in the cool and cold room can be found in Table 8.

Table 8: Heat flows

Heat Load	**Cold Room**	**Cool Room**
Conduction through walls	2,878	2,186
Heat of respiration	1,584	567
Field heat	19,711	7,242
Service load	2,302	2,186
Total heat load	***26,475***	***12,181***

Now that the total heat load has been calculated, the refrigeration and ventilation system can be designed.

Design Alternatives

The objective of the project is to evaluate and present design alternatives for a cold storage unit and compare the economic and environmental effects of each design. This project investigates several design alternatives for cooling, ventilating and insulating a cold cellar basement. The maximum volume of produce stored is 32,250 lbs in 576 containers with a calculated cellar volume of 13,200 ft^3. These calculations can be found in Appendix B.

At the SOF the current above ground refrigeration system has two separate cooling units, one for storage of cold and moist produce at temperatures. The system utilizes basic refrigeration with compressors and condensers and uses electricity.

Design - Insulation

In order to minimize the heat gained through the walls via conduction, the R-value must be optimized. However, there will be a point where the cost of materials no longer justifies the additional gains in R-value. Additionally, the practical requirements of the building design need to be taken into consideration.

The materials reviewed for the additional insulation were fiberglass, particleboard, foam board and polyurethane. Fiberglass was chosen as it has a very high R-value at a low cost. Particleboard was chosen because it is cheap and readily available. Polyurethane was chosen for its ability to handle moisture.

To establish an initial insulation design, the industry standard for cold rooms was consulted. The recommended minimum R-value was 28, with at least 4 inches of extruded polystyrene included, which has an R-value of 5 per inch. Additional insulation is necessary to reach the value of 28 (Gary, 2013)

Fiberglass insulation works best in construction with walls and foundations. It fits well between studs, joints, and beams. It can also be used in the floors and ceilings. There are also zero CFC's used in the manufacturing process. This type of insulation is also relatively inexpensive for the R-value it provides. Negative aspects of fiberglass include that it is loose fill, it loses the majority of its insulative value when wet, and the R-value is slightly less than foam insulation.

Foam boards like polystyrene and polyurethane are rigid panel insulation. They work well throughout most buildings top to bottom. The boards provide good thermal resistance and reduce heat conduction, providing a high R-value for a relatively small thickness (USDOEA, 2010). However, CFC's are generated in the production of foam insulation, which degrade the ozone layer.

Due to the cool nature of the unit, the air surrounding it will be warmer and hold more moisture. Therefore, the vapor barriers need to be to the outside. In this case, the extruded polystyrene will be on the outside, with any supplemental fiberglass insulation on the inner layer.

Insulation Selection

In addition the industry standards for insulating cold rooms, there is the need for additional insulation to increase the R-value. Several available building materials were evaluated by cost and R-value, and are presented in Table 9.

Table 9: List of building material R-values (USDOEA, 2010)

Material	Thickness	R-value	Total R-Value	Cost/ft²	Cost/ ft²/R-Value
	in.	*Value/in.*	*Value*	*$/ft²*	*$/ft²/R-value*
Fiberglass batt	3.5	3.7	13.0	0.30-0.40	**0.02**
	8.0	3.7	30.0	0.60-1.00	0.03
Loose fill such as fiberglass, cellulose, and mineral wool	8.0	3.8	30.0	0.45-1.35	0.03
		3.8	50.0	0.75-2.25	
Open cell polyurethane spray foam	3.5	3.6	12.6	0.17	0.17
Closed cell polyurethane spray foam	1.0	6.5	6.5	1.30-2.00	0.25
Expanded polystyrene foam board	1.0	4.1	4.1	0.20-0.35	0.07
Extruded polystyrene foam board	1.0	5.0	5.0	0.40-0.55	0.10
Polyisocyanurate foam board	1.0	6.5	6.5	0.60-0.70	0.10

Several insulation materials were analyzed. The main factors considered were the R-value and cost. An ideal insulation has a high R-value and a low cost. Materials were normalized for comparison by dividing cost by R-value. The insulations the group chose to review for the additional insulation were fiberglass, particle board, foam board and polyurethane. For this deliverable, the group selected 3.5-inch thick fiberglass for the additional insulation with an R-value of 13 (USA, 2012). Thus, the building materials are 12 inches concrete, 4 inches of extruded polystyrene and 3.5 inches of polystyrene with a total R-value 34.28 for the walls and ceiling. Fiberglass needs to be on the inside of the unit so it does not come into contact with the moist outside air. Additionally, 1 inch blue board will be used to insulate the floor.

The original calculations evaluated the industry standard R-value of 28 as a placeholder. Now, with the additional insulation selected, the R-value is 34.28. With the additional insulation added, the heat gained due to conduction was reduced by 15% in the cold cellar and 13% in the cool. Therefore, this new R-value will be used for the rest of the calculations.

Designs- Refrigeration

Supplemental refrigeration will be required to remove the field heat within 24 hours. This is necessary due to the high volumes of produce the farm expects. There are multiple alternatives under consideration for the supplemental refrigeration systems. Three designs being evaluated for implementation include a CoolBot attached to an air conditioner and a small-scale refrigeration system. The potential for only using the cooling effects of the ground will also be evaluated.

CoolBot

A CoolBot is an attachable controller device that manipulates an air conditioner into running continuously as a compressor. The CoolBot can maintain temperatures of 35Fwhile using only half the electricity that an equally sized standard compressor would require (Munzer, 2012). The savings in electricity derive from using fewer fans. A standard refrigerated container unit includes 4 to 6 fans running continuously inside and an extra 1to 2 outside. A window AC unit only has one fan that doesn't have to run continuously if the unit is in energy saver mode (CoolBot, 2006). This is accomplished by attaching a heating element to the air conditioner's temperature sensor causing the compressor to run longer. To prevent freezing, a second sensor idles the unit when the temperature drops too low, then restarts the unit once it thaws again. Visits to local farmers, including Titus Farms, have confirmed that the CoolBot can successfully be used to make up the 10-20 F between the underground temperature and the desired temperature at greatly reduced energy costs compared to traditional refrigeration. The CoolBot website reports that the CoolBot refrigeration system is at minimum 25% cheaper than a conventional modern walk in unit (CoolBot, 2006).

Conventional Refrigeration

Another alternative is to purchase a standard refrigeration unit. This would be a complete industrial refrigeration unit consisting of a compressor, condenser, expansion valve, and an evaporator with refrigerant R-134a (Cengel and Boles, 2011). The unit is similar to the one currently being used in the above ground refrigeration system, but it would be smaller because of the improved design. These systems are more expensive than CoolBots and use more energy to cool a similar space, due to the high operating costs of multiple fans. (Munzer, 2012).

No Refrigeration

Without a supplemental refrigeration system it is still possible to maintain cool conditions. Utilizing the cooling of the earth along with high R-value insulation materials would help regulate conditions. Evaporative cooling can also be used in the ventilation system along with bringing in cool night air. However, the main drawback of the system is the inability to quickly remove field heat. The produce deteriorates faster if the field heat is not removed quickly. For example, strawberries experience a 10% increase in decay for every hour cooling is delayed (Saltveit, 2013).

Refrigeration Selection

There are several alternatives for how the unit will be refrigerated including, an industrial size cooling unit, CoolBot- AC unit and no refrigeration. The parameters used to assess the refrigerator systems are functionality, energy use, environmental impact, and the initial cost.

The functionality is the most important parameter with a weight of 40% as the refrigeration system must be able to quickly and dependably adjust the cellars to the proper temperature range before any produce is lost due to spoiling. The energy use was given a weight of 30% because reducing energy use in food storage is the main goal of the project. The environmental impact will be analyzed with a weight of 15% to determine which refrigeration system has a lower impact based on the materials used and the energy usage. Finally, the initial cost was given a low weight of 15% because the initial cost is not as important as reducing energy use and long-term costs. However, there is a large difference between the cost of an industrial sized cooling system and a CoolBot. Therefore, the energy use will also be analyzed to determine which system has a lower overall cost. A decision matrix, as show in Table 10, was then made to determine which refrigeration system would work best at the SOF.

Table 10: Decision matrix for refrigeration system

	Functionality	**Energy Use**	**Environmental**	**Initial Cost**	**Total**
Weight	*.40*	*.30*	*.15*	*.15*	*1.0*
Industrial Refrigerator	10	4	5	5	6.7
CoolBot- AC Unit	10	9	8	7	**8.95**
No Refrigeration	2	10	10	10	6.8

The industrial size refrigeration unit, currently used at the SOF, is able to cool the produce and maintain a constant temperature. Where the industrial refrigeration unit falls short is the initial cost and energy usage. The price of an industrial refrigeration unit is upwards of

$1,500 (Grainger, n.d.). In addition, the electricity needed to run the unit is very large due to several fans that are continuously running to make the unit work. This additional electricity increases the operating costs and carbon footprint of the farm. The industrial system will work but is relatively inefficient.

There are several benefits to using the CoolBot system. For instance, a CoolBot system sells for $300 and functions with an AC unit that runs from $300 to $1,000, depending on the size of the AC unit required. A traditional walk-in cooler compressor sells for $2,500. Therefore, the initial cost is slightly lower for the CoolBot system, which received a 7 compared to the 5 of the industrial refrigerator. Additionally, the CoolBot system does not have multiple fans. These fans make up the bulk of the operating cost, roughly 60%. The fans also tend to dry out the air, which in turn dries out the vegetables, or dries out the evaporative cooling pad faster than an AC unit would**.** The CoolBot received a better environmental score because it uses less electricity then an industrial refrigeration system. This is the reason the CoolBot received a much better score in the energy use category. Both designs received a 10 for functionality because they have been shown to be able to successfully cool the cellar. Furthermore, the CoolBot concept has been proven to work at the local Titus Farms.

When using a CoolBot it is important to select a compatible air conditioner. According to the manufacturer, the CoolBot works with either "Thru-the-Wall" or window air conditioners. But, it is CoolBot's recommendation to use window air conditioners because of their lower operating costs. Whatever air conditioner brand is chosen, the air conditioning units must have a digital display. (CoolBot, 2006)

The CoolBot website recommends use of two brands of window air conditioning units: GE and HAIER. The GE brand is considered the better of the two, but it is also more expensive than the HAIER unit. The HAIER unit sometimes has electrical problems. Though many other brands were examined, either GE or HAIER air conditioners are recommended for the CoolBot to work most effectively.

The no refrigeration system had many positive design parameters; zero initial cost, energy usage or carbon footprint. However, the design is not functional, as it is unable to quickly remove field heat. The no refrigeration system is only practical for cooler seasons, and for storing produce that has already had the field heat removed.

For example, in August the majority of produce is introduced to the unit. The total heat load of the room is 14,000 BTU/hr. The basement will be in contact with soil that is around 55 degrees. How will this heat be removed and lowered without a refrigeration system? The answer is that it will stay in the produce and cause spoilage.

Design -Ventilation Types

In order to maintain temperature and humidity conditions in the room, a ventilation system is required. Proper ventilation aids in the cooling of produce by circulating air throughout the room. Ethylene gas, produced in the ripening process, is removed to prevent produce ripening too quickly. Typically root cellars use very rudimentary ventilation systems. These will be investigated and compared with a system used in industrial cold storage. The two ventilation systems that will be investigated are a dual vent system and an evaporative cooling system.

Dual Vent System

Basement cellars typically utilize a dual vent system, with one vent near the floor and the other near the ceiling to ensure proper air circulation. An example of a simple root cellar ventilation system can be found in Figure 8. A mesh filter is used on both ends of the tube to prevent contaminants and wildlife from entering. This system would require wetting the concrete floor to raise humidity, and a dehumidifier would be required to lower the humidity. There is also a valve so the vent can be closed or opened.

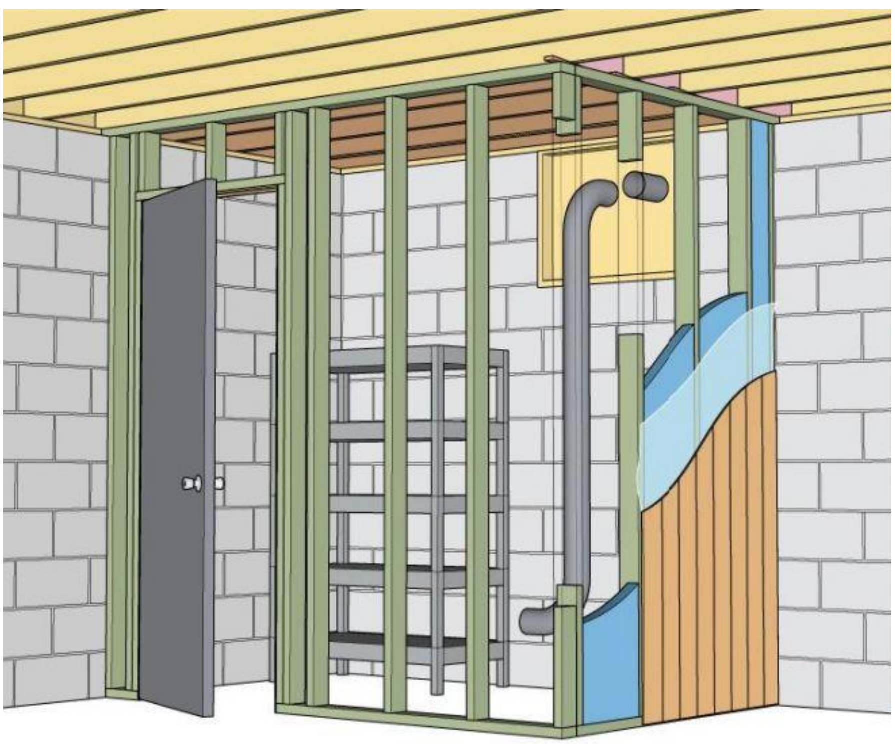

Figure 8: Basic ventilation system in a cold cellar (Trandem, 2013)

Evaporative Cooling System

A ventilation system that incorporates evaporative cooling is a strong alternative to the dual vent system. The system would be composed of these main components, air intake, louvers, axial fans for air circulation, evaporative cooling pad, exhaust, and temperature/humidity sensors. Air is brought in at the intake, adjustable with mechanical louvers. Then, axial fans blow the air across an evaporative cooling pad, lowering the temperature and raising humidity. The air is circulated around the room before it either re-enters the ventilation system or exits through the exhaust. Temperature and humidity sensors are positioned at the air intake and in the storage area. These sensors can be linked to the louvers, fans and potentially CoolBots using an automated computer system.

Ventilation Selection

Ventilation design criteria were developed in order to compare the evaporative cooling ventilation system to the dual vent system. The ventilation system is responsible for providing air circulation, while also helping to cool the unit and maintain humidity levels. The client expressed that the ability to maintain cellar conditions is the most important ventilation criteria. Therefore the air circulation criteria received a weight of 40%. The ability of the ventilation system to provide cooling and raise humidity was evaluated with the climate control criteria with a weight of 40%. The initial and operating costs each received a weight of 10%. A decision matrix, as show in Table 11, was then made to determine which ventilation system would work best at the SOF.

Table 11: Decision matrix for ventilation system

	Air Circulation	**Climate Control**	**Initial Cost**	**Operating Cost**	**Total**
Weight	*.40*	*.40*	*.10*	*.10*	*1.0*
Evaporative Cooling System	10	10	2	5	**8.7**
Dual Vent System	6	6	9	10	6.7

The evaporative cooling system received 10's for ability to circulate air and maintain the humidity of the room. This is by far the most functional system and allows the utilization of cool night air along with evaporative cooling. However, the system will require fans, raising the operating cost and is somewhat expensive to begin with. The client is willing to pay the extra cost if it means a self-regulating ventilation system that can always maintain conditions.

The dual vent system does not circulate air as the evaporative cooling system therefore it received a 6 in the category. However, for the system to circulate as effectively as the evaporative cooling system requires purchasing additional fans. The dual vent system received a six for climate control because although it allows drawing in night air to cool the unit, it does nothing to manage humidity levels. The dual vent system is much cheaper to purchase, as it is literally two tubes, so it received a score of nine. To operate the system requires no electricity, it is simply the farmer opening the vent at night. Therefore the operating costs received a ten.

The final design selected for the ventilation system is the evaporative cooling ventilation system. The supplemental refrigeration is a CoolBot controller attached to 'through the wall' air conditioning unit. The insulations selected uses polystyrene and fiberglass. These have been selected to build the most efficient, low cost cellar possible.

Ventilation Details

The ventilation system design is shown in Figure 9. The design consists of four main components, the air intake, a fan, an evaporative cooling pad and the exhaust (Ventilation Fundamentals, 2014). All components besides the exhaust will be contained within the ventilation recirculation room along with the CoolBot. The CoolBot will only be operating when additional cooling is required, such as during field heat removal or during a very hot day. The client can also choose to install a FANCOM system, which automates the fans, intake and CoolBot to maintain conditions.

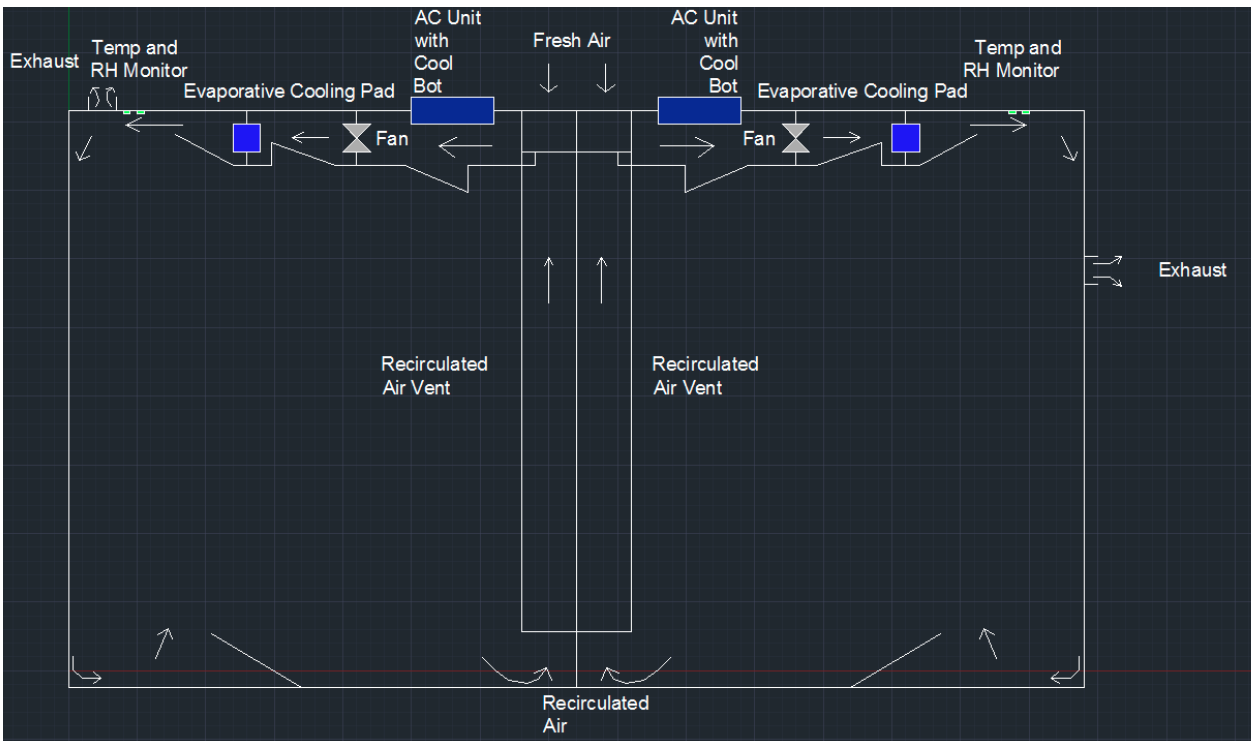

Figure 9: Plan view of the ventilation system

The air intake will be accessing air from an egress window with a louver at the entrance. Air will enter the ventilation room through the intake. An ISO-Door™ from Techmark will be used to electronically control the amount of air entering the room based on temperature and humidity sensor data (Fresh, 2014). Air can also be drawn in through the CoolBot unit, with the CoolBot ejecting waste heat outside through an egress window. The air intake system contributes a static pressure of 0.125 inches (Forbush, 2014).

Once the air enters the room, it is then mixed with the re-circulating air from the room in the mixing chamber, before being blown with a direct drive axial fan through the evaporative cooling pad and into the storage room, where the shelving is arranged to ensure proper air circulation. Then the air either exits through the exhaust or is pulled through the recirculating corridor back to the ventilation room. The ventilation room has doors for maintenance access. The door hinges are oriented to open in a way that the pressure created by the fan will keep them shut tightly (Fresh Air Intake n.d.).

To size the fan, evaporative cooling pad and intake vent, the airflow requirements for the room in cubic feet per minute (CFM) must be calculated. Due to different respiration rates and produce loads the rooms have different CFM requirements (Fan Sizing, 2014).

To calculate the CFM required for our ventilation system USDA handbook 66 was consulted. Potatoes were used as a benchmark because they are known to require 1 CFM per hundred-weight (100 lbs) while respiring at a rate of 10 mg/kg×hr. Therefore referencing handbook 66 and comparing the respiration rate of other produce to potatoes allows for CFM calculations for every produce. The upper rate of the respiration range was used, at the temperature of storage. Tables 12 and 13 represent the maximum CFM loads required for each room. With this information and the static pressure, equipment can be sized.

Table 12: CFM calculation of large room

Cold Produce	**Respiration Rate (mg/kg×hr)**	**Ratio/Potatoes**	**# 100 weights**	**CFM required**
Beets	10	1.0	35	35
Cabbage	12	1.2	45	54
Carrots	26	2.6	60	156
Celeriac	15	1.5	10	15
Garlic	33	3.3	8	25
Onions	4	0.4	30	12
Potatoes	10	1.0	70	70
Rutabagas	10	1.0	15	15
Total			273	**382**

Table 13: CFM calculation of small room

Cool Produce	Respiration Rate (mg/kg×hr)	Ratio/Potatoes	# 100weights	CFM required
Winter Squash	12.2	1.22	50	61
Total			120	**61**

The other information required to size equipment is the static pressure the fan will have to overcome. The evaporative cooling pad will be using 18 inch media with an expected air velocity of 500 FPM. This produces a static pressure of 0.3 inch. The static pressure was calculated to be 0.125 inch at the fresh air inlet 0.3 inch at the evaporative cooling pad with an added 0.075 inch as a cushion. This results in a total static pressure of 0.5 inch (Forbush, 2014).

Using the CFM and the static pressure the fan can be selected. The fan selected is a direct drive axial fan because they are economical for low volume (2,000 CFM) and low static pressure (0.50 inch or less) (Ventilation, 2005). They require little maintenance and can be used with a speed control to vary the CFM based on produce load. (Truman, 2014) The fan for the cold room must deliver at least 382 CFM at 0.5 inch static pressure and the cool room fan must deliver at least 131 CFM at 0.5 inch static pressure. The fan selected for the cold room is a 500 CFM axial fan from Dayton and the fan selected for the cool room is a 230 CFM axial fan from Dayton. (Fan, 2014) Fans selected are 230 Volt instead of 115 so the current will be lower and thus, a lower a resistive loss (Surbrook, 2014).

The evaporative cooling pad was designed to be tall and thin. The area of the pad was calculated for an FPM of 500 or below (Forbush, 2014). It is important that the air velocity is low through the pad to ensure that the air gets moisturized and to extend the lifespan of the pad. Dividing the 312 CFM/500 FPM yields that the pad must be at least 0.632 $feet^2$. Therefore the size of the pad is at 1.0 ft^2. Since the design should be tall and thin the dimensions are 18 inches tall and 12 inches wide. The media is 18 inches thick. The evaporative cooling efficiency is around 98% (Munters, 1990). The pad requires a sump pump to maintain proper moisture levels. This will be a small, inexpensive pump that the SOF can install on-site for cheaper than hiring a professional. The evaporative cooling pad could be replaced with a few air-assisted nozzles if the space was to be converted to a mushroom growing facility.

Ventilation Analysis

To compare ventilation designs, the effectiveness of the designs must be evaluated. Enviro-weather data was used to trace the air quality through the system. Average weather data was accumulated for the relevant months of operation (Enviro-weather). Psychrometric charts were consulted to estimate the wet bulb temperature, enthalpy and humidity ratio (Cengel, 2008). The air properties for selected months are presented in Table 14.

Table 14: Inlet air properties

Month	**Hourly Average T**	**Hourly Average RH**	**Wet bulb**	**Enthalpy**	**Specific Volume**
	F	*%*	*F*	*BTU/lb*	*Ft^3/lb*
February	16.3	71.8	14.7	5.3	12
March	30.6	70.9	27.9	10	12.4
April/May	52.3	64.6	46.4	18.4	13
July/August	69.0	72.4	63	28.5	13.6
Nov/Dec	30.5	75.0	28.2	10.2	12.4

Now that the air quality post evaporative cooling is known, the effect of mixing the ventilated air stream with the rest of the cold storage unit can be calculated. This can be described using equations for the adiabatic mixing of two airstreams (Cengel, 2008). A visual depiction of adiabatic mixing is shown in Figure 10. The equation describing the air property transformation is in Equation 18.

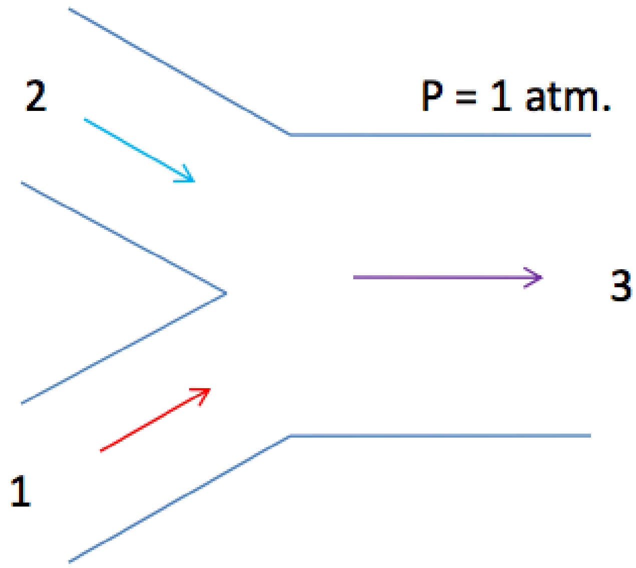

Figure 10: Depicts the air flow at 1atm

Where stream 1 is the room air, stream 2 is the ventilation air and stream 3 is the mixed air.

$$\frac{\dot{m}_{a1}}{\dot{m}_{a2}} = \frac{w_2 - w_3}{w_3 - w_1} = \frac{h_2 - h_3}{h_3 - h_1} \quad \text{(Eq. 18)}$$

Where *m* is the mass flow rate of air, *w* is the work per unit mass and *h* is the enthalpy. To calculate *m*, the volumetric flow rate is divided by the specific volume of the air, as described in Equation 19.

$$\frac{\dot{V}}{v} = \dot{m} \quad \text{(Eq.19)}$$

Where $\boldsymbol{v}$ is the specific volume of air, and is calculated using Equation 20.

$$v_{da} = (1 + x\, R_w / R_a)\, R_a\, T / p \qquad (Eq. 20)$$

Where $\boldsymbol{v}_{\mathbf{da}}$ is the specific volume of dry air, x is the humidity ratio, R_w and Ra are constants, T is temperature and p is the pressure.

The CFM required for the large room is 382 CFM. This will be used for the volumetric flow rate of air in the room. The large room, with conditions of 40 F and 85% Relative humidity yields an enthalpy value of 14.4 BTU/per pound of dry air. This will be used for h_1. The axial fan in the large room delivers 500 CFM; this will be used for the volumetric flow rate of air in the ventilation system. The effect of mixing was calculated and is presented in Table 15. Additionally, the mixing chamber will have a lot of condensation, and will require a drain. A way to recirculate water is to attach the drain in the mixing chamber to the water pump on the evaporative cooling pad.

Table 15: Flow rate and enthalpy of ventilation system

Month	**Flow rate**	**h_3**	**T_{3-DB}**	**T_{3-WB}**
	lbs/ft	*BTU/lbs*	*F*	*F*
February	41.7	9.72	28	26.3
March	40.3	12.2	36	32.7
April/May	38.8	16.4	47.5	41.7
July/August	37.0	21.2	53	50.2
November/December	40.3	12.3	36	32.72
Room	39.4			

The effect on the air temperature is described by equation 21.

$$T_{LA} = T_{DB} - ((T_{DB} - T_{WB}) \times E) \qquad (Eq. 21)$$

Where T_{LA} is the temperature of the air as it leaves the evaporative cooler, T_{DB} is the dry bulb temperature of incoming air, T_{WB} is the wet bulb temperature of incoming air and E is the efficiency of the evaporative cooler. The efficiency of the cooler is 98% (Munters, 1990).

The evaporative cooling process follows the same curve as the adiabatic saturation process, so the wet bulb temperature and enthalpy values can be assumed to remain constant (Cengel, 2008) T_{LA} can be used with the wet bulb temperature to calculate air properties post evaporative cooling, depicted in Table 16. For conditions such as February, where the temperature post mixing is below freezing, the air intake should be closed or the louvers adjusted to lower the air influx.

Table 16: Air properties post evaporative cooling

Month	**T_{DB} Inlet**	**T_{DB} post mixing**	**T_{LA} DB**
	F	*F*	*F*
February	16.3	28	Freeze
March	30.6	36	32.8
April/May	52.3	47.5	41.8
July/August	69.0	53	50.3
Nov/Dec	30.5	36	32.8

Design Optimization

There are several aspects of the original design that can be optimized. These include the room dimensions and the functionality of the rooms.

It was determined that in the fall harvesting season there was very little produce being stored in the cool room, and in the summer there was very little produce being stored in the cold room. Therefore, in each season there is an oversized storage room. Minimizing one of the rooms into a smaller space will reduce the material cost and lower the electricity required for cooling.

Therefore an optimization to minimize the surface area of the walls and volume of both the cold and cool rooms can be made by converting the rooms to a large and small room. The CoolBot digital thermostat will be used to switch the temperature of the rooms between seasons.

The client was consulted to determine if these produce loads would be predictive of the future. The client stated that the farm has no room for expansion, and that the produce loads given to us are very high, and that any design that can accommodate the current produce load will be acceptable in the future.

After rearranging the setup of the cool room and changing the shelving a new optimized room was designed. From now on the cool room will be referred to as the "small room" which will store the cool produce in the fall and cold produce in the summer. This is a critical conceptual distinction, as the client will now alternate the room climate depending on the season. The new, optimized dimension of the small room is now 18ft. x 14ft. x 8ft. as shown in Figure 11. The second room will now be called the "large room". The large room will store cold produce in the fall and cool produce in the summer. Figure 12 shows the layout of the large room, and Table17 describes the differences between the old and new room.

Table 13: Differences between the old room (cool room) and new room (small room)

	Original cool room	**New cool room "Small room"**
Dimensions	32 ft x 22 ft x 8 ft	18 ft x 14 ft x 8 ft
Volume	5,632 ft^3	2,016 ft^3
Percent Volume reduction		64%
Construction savings		$1,320

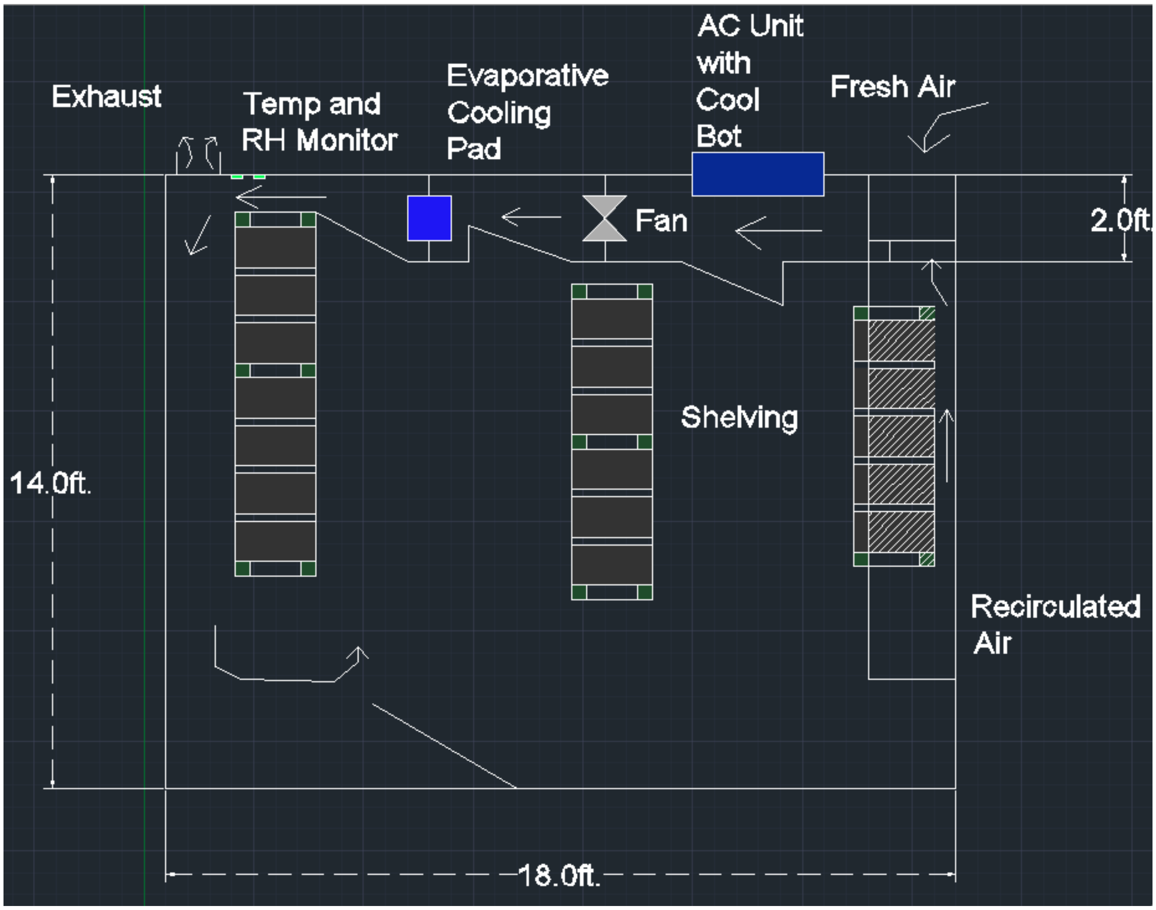

Figure 11: Plan view of optimized small room

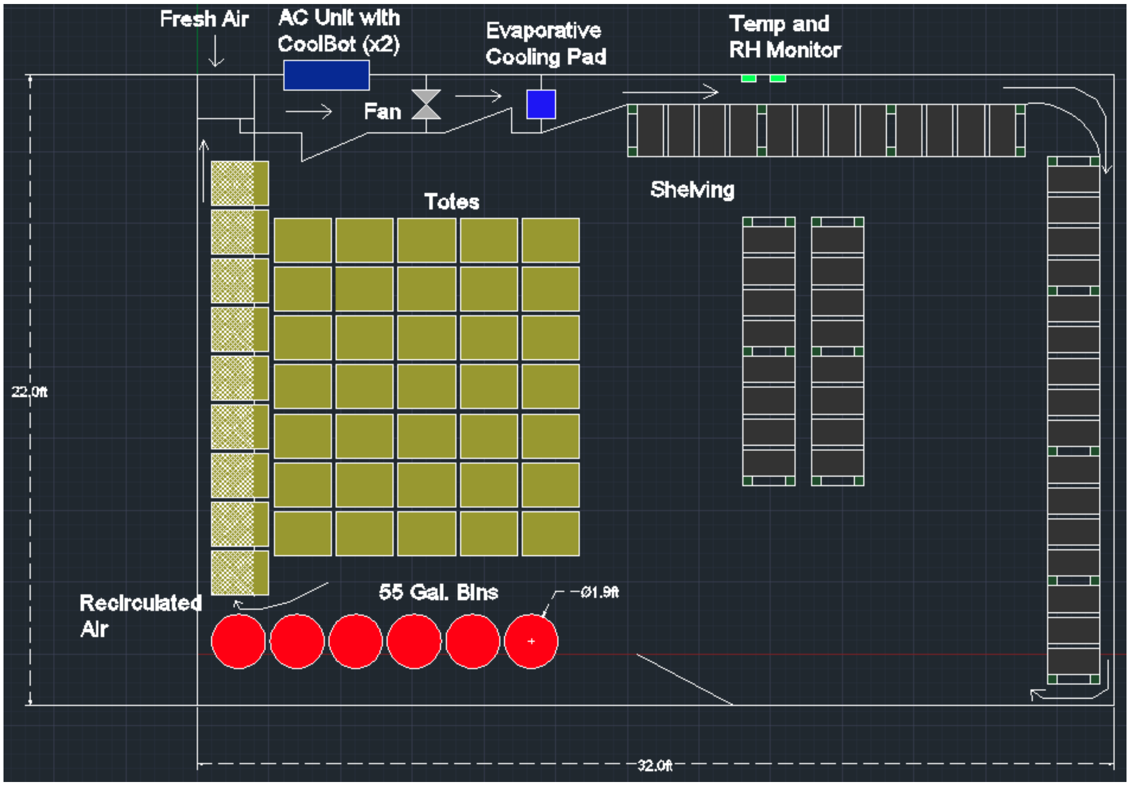

Figure 12: Plan view of the large room optimized

The new dimensions of the small room reduced the volume and area by 64%. Figure 13 shows the new plan view layout of the basement with the large room and optimized small room. By reducing the room size not only does it cut down on construction cost but it also cuts down on the conductive heat loss through the walls in the basement. Minimizing the room size reduces construction costs by $1,230, with the majority of savings derived from reducing the insulation costs. It was calculated that by changing the room sizes the conduction through the walls was reduced by roughly 60% in the cool room. This significantly lowered the amount of BTUs needed for the AC unit.

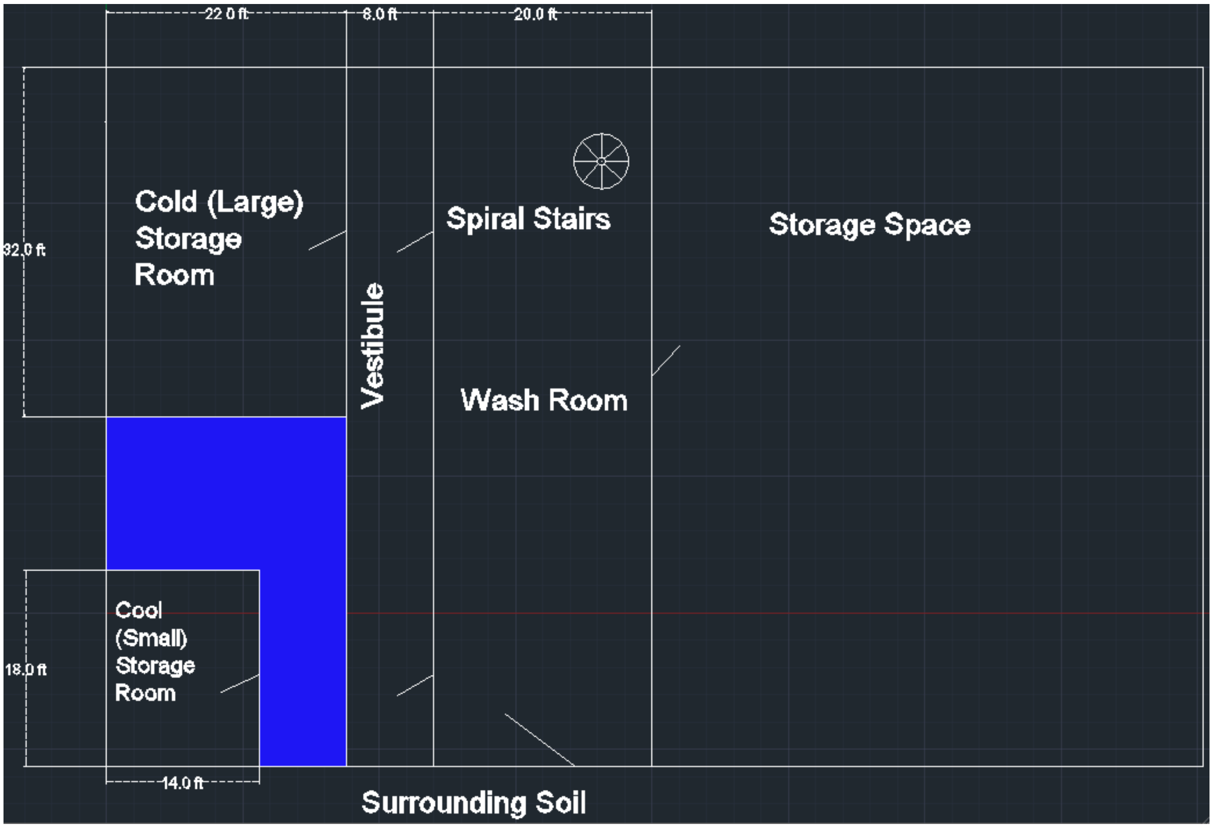

Figure 13: Plan view of the two rooms optimized

Heat Load by Month

The heat load was broken down by month in order to calculate operating costs. Figure 14 through 19 depict the heat load for every day of the fall storage season.

Figure 13 depicts the heat load for the entire storage season. This shows the dramatic effect of removing field heat when produce is initially brought into the cellar and the effects of outdoor changing temperatures, as well as the gradual depletion of produce in the storage space. Table 18 details the produce introduction and removal rates, as well as the average monthly temperatures. In depth monthly heat load graphs are depicted in Figure 14-19.

Table 14: Storage temperature and bi-weekly depletion

Produce	**Month introduced to Storage Room**	**Bi-weekly depletion (lb)**
Beets	August (74.1 F)	100
Cabbage	August (89.5 F)	320
Garlic	August (74.1 F)	30
Onions	August (74.1 F)	160
Rutabagas	August (74.1 F)	100
Celeriac	October (69.9 F)	100
Potatoes	October (69.9 F)	160
Carrots	November (49.1 F)	160

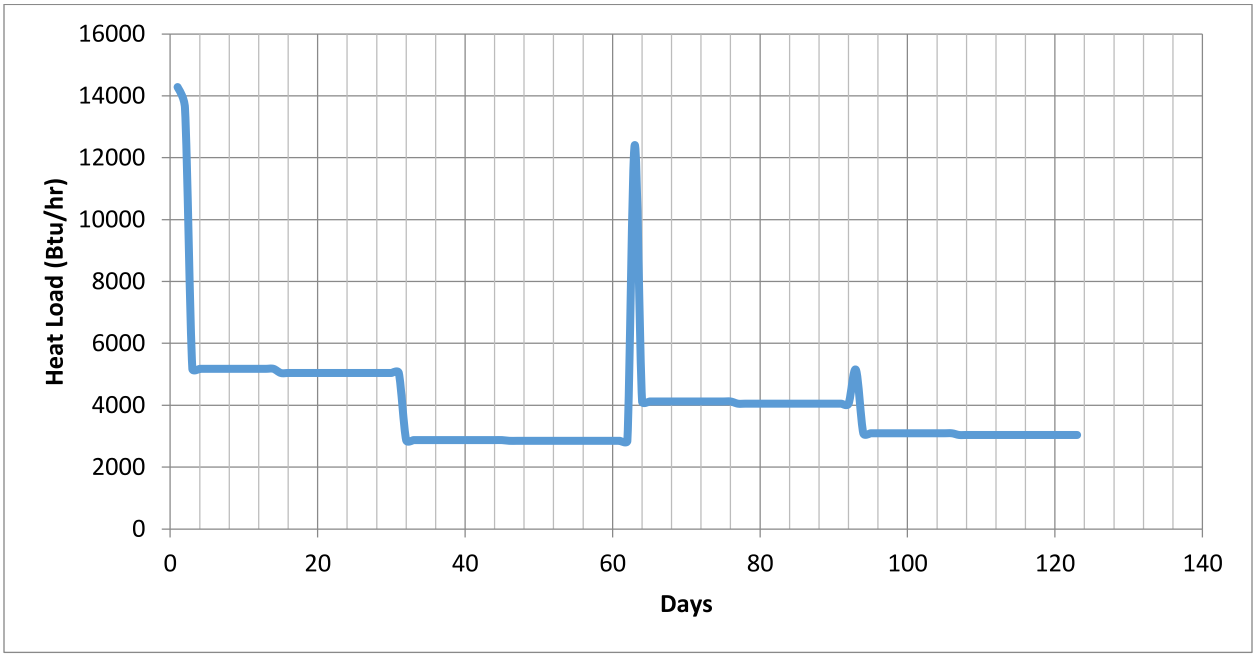

Figure 14: Heat load from August to November

Figure 15 depicts the heat load during the month of August. It was assumed the farmers would put beets, onions and rutabagas on the first day, then cabbage and garlic the second day to ensure rapid cooling. As the graph depicts the heat load drops dramatically once the produce is cooled. The SOF sells 100 pounds of beets, 320 pounds of cabbage, 30 pounds of garlic, 160 pounds of onions, and 100 pounds of rutabagas every two weeks. Once the produce is sold on the fourteenth day the amount of respiration heat is reduced due to the diminishing poundage of produce. The produce is sold at this rate for the duration of the product storage time.

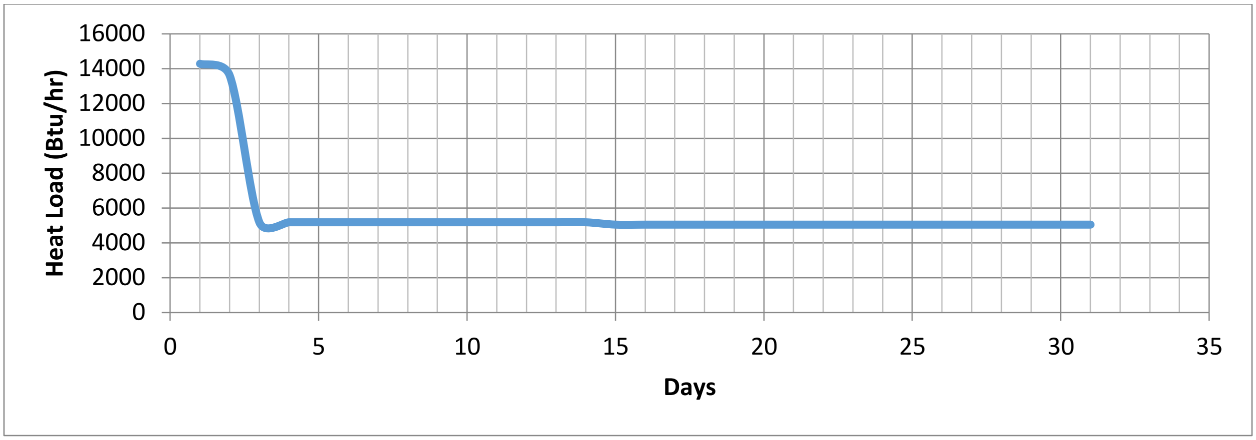

Figure 15: Heat load for August

Figure 16 depicts the September heat load. Zero produce is brought in during September, but again the produce is sold on the fourteenth day. This graph shows the deminishing heat load due to the depletion of produce on a biweekly basis.

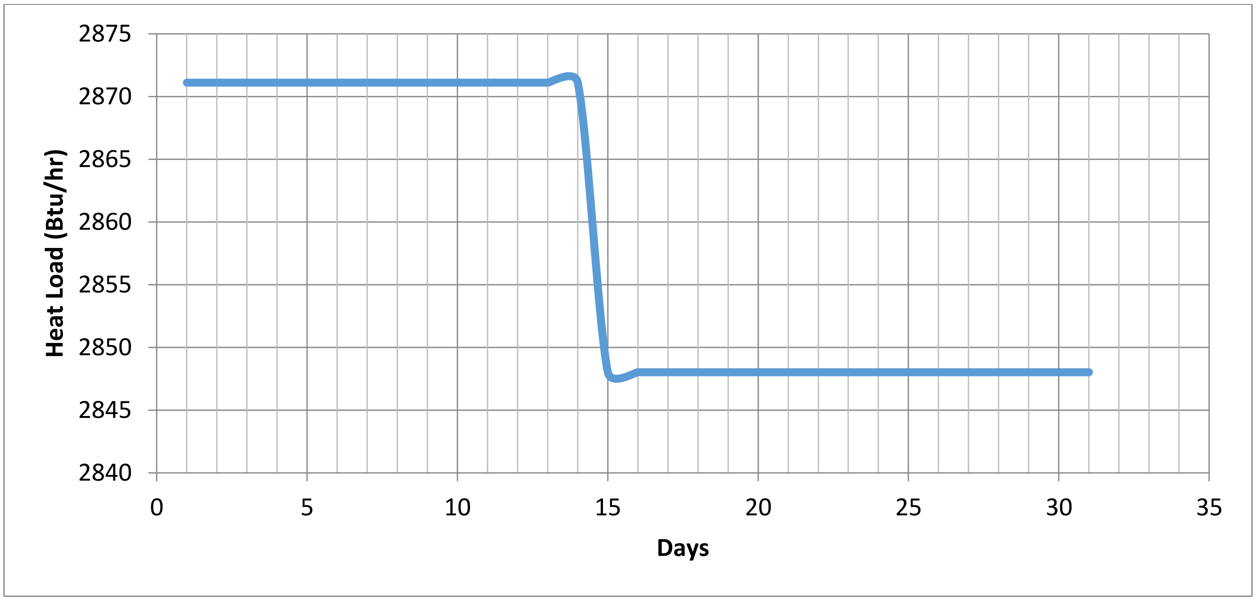

Figure 16: Heat load for September

Figure 17 depicts the heat load in the month of October. It was assumed that potaotes and celeriac are brought in on the first day. The SOF sells 100 pounds of celeriac and 160 pounds of potatoes on the fourteenth day in addition to the produce sales detailed for August. Again, the same trend is observed once the field heat is removed and less produce is being stored.

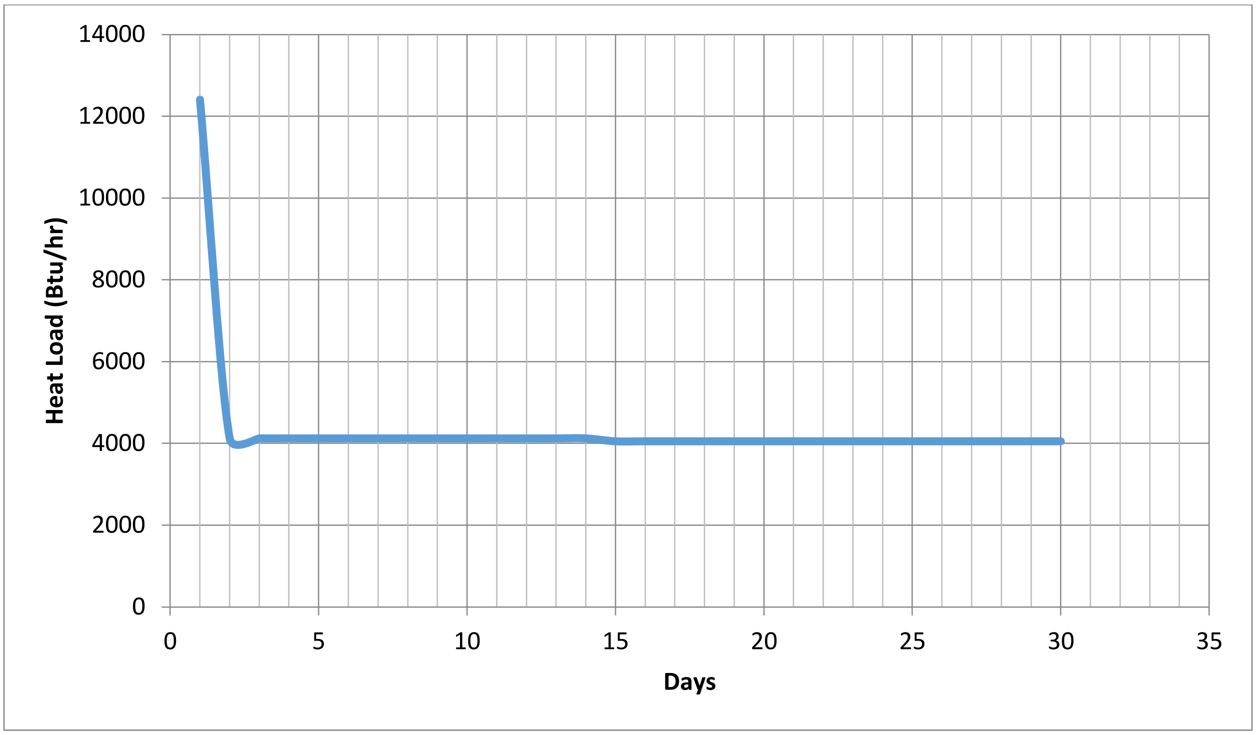

Figure 17: Heat load for October

Figure 18 depicts the heat load in the month of November. On the first of the month it was assumed carrots are brought into the cellar. The SOF sells 160 pounds of carrots on the fourteenth day, in addition to the produce sales detailed in the previous months. The graph countinues the trend from the previous months.

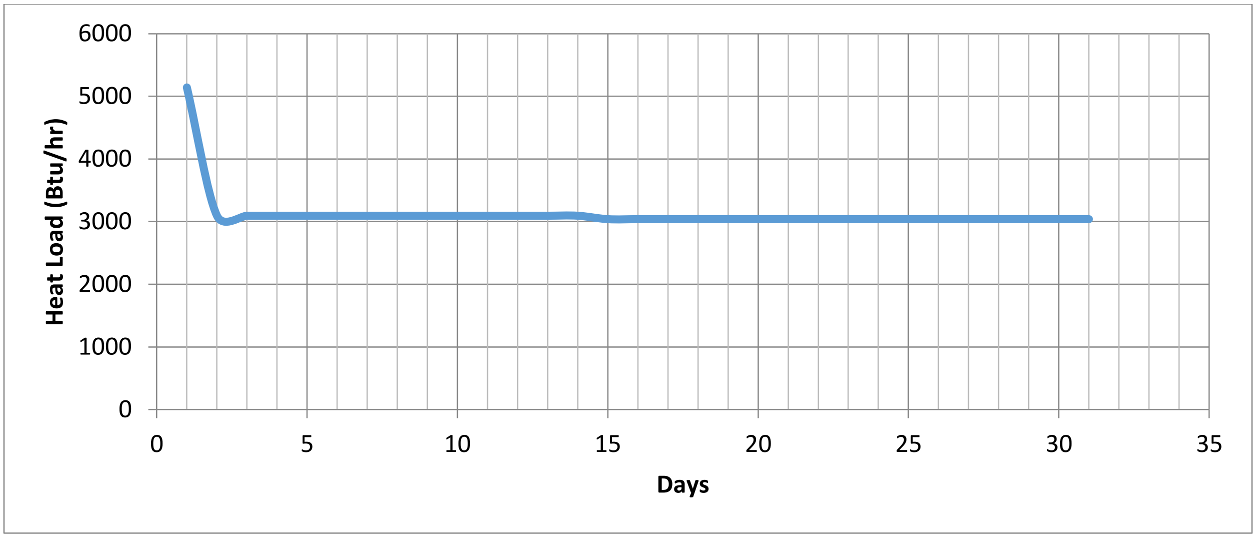

Figure 18: Heat load for November

Figure 19 shows the effect of changing outdoor temperatures each month coupled with the changed poundage of produce, whether being brought in or sold. The depiction of heat load without field heat is shown in Figure 19.

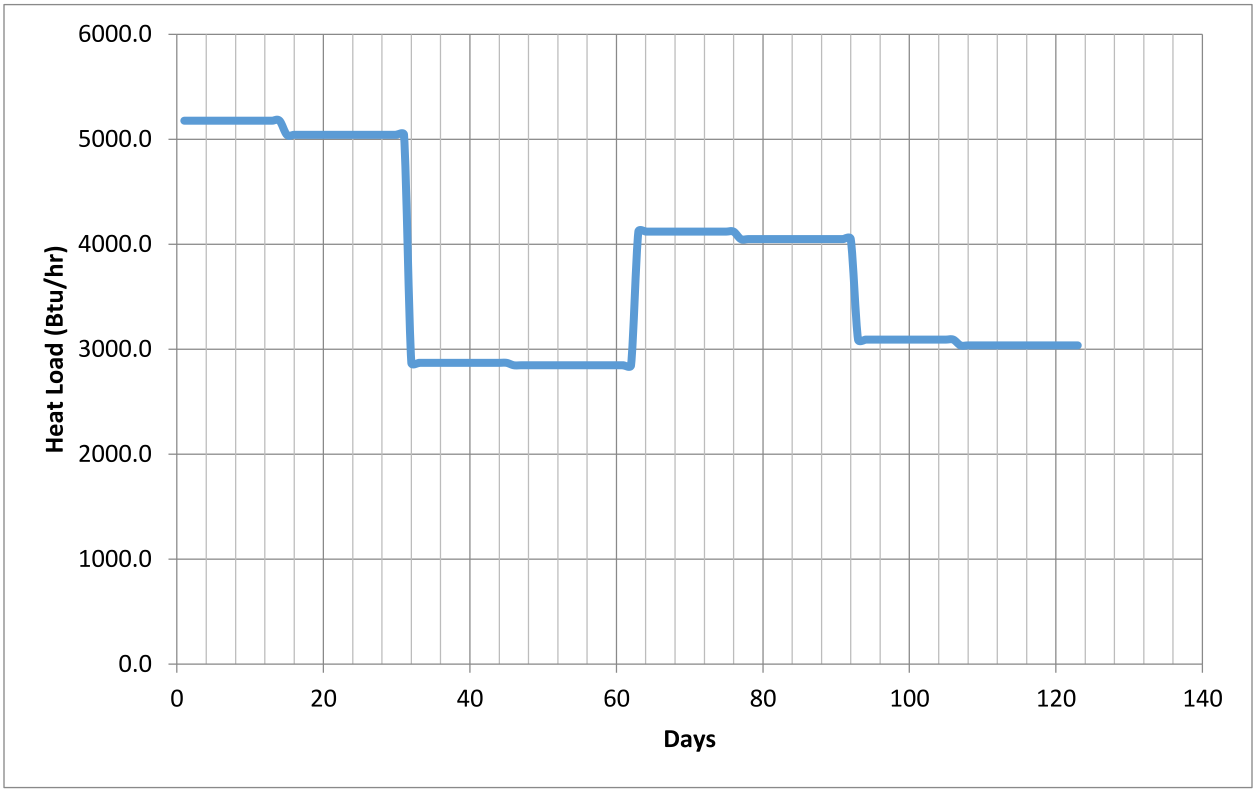

Figure 2: Heat load from August to November without the field heat

Economics

Determining the economic feasibility of building a cold storage unit requires analysis of the construction expenses and potential savings. The total cost to build the cold storage unit will be composed of three main categories; building construction, cold storage unit construction and mechanical equipment cost. All savings generated derive from the unit's reduction in electricity used for refrigeration. Labor savings will be negligible, or lessened, due to the decreased transport distance and pallet jack.

In order to obtain pricing estimates for the ventilation system, all components must be considered. The evaporative cooling pads chosen for this economic analysis came in a pack of five, as they wear out over time and eventually need to be replaced. Evaporative cooling pads also require a simple water pump to maintain moisture levels.

In order to monitor and control the climate of the room, combined temperature and humidity sensors must be installed in the room and at the air intake. These sensors can be utilized to manually adjust the airflow of the room, or they can be wired into a fully automated system. Techmark sells the fully automated FANCOM system for $12,000. The FANCOM system would adjust the louvers, fans and CoolBots continuously to maintain optimal storage conditions. Alternatively, a worker can be trained to use psychometric chart readings to manually adjust the louvers and CoolBot according to weather fluctuations. However, this will be time consuming and raise labor costs, as well as increasing the risk of produce spoilage. The automated system will reduce produce losses; the exact effect cannot be calculated. The client inquired what the payback period would be if the FANCOM system was implemented.

The only cost for the refrigeration system is for the CoolBots and the air conditioning units. A 15,000 BTU window air conditioner attached to a CoolBot will be able to handle the heat load in the small room. However, the large room has a much higher volume of air, and will require two 15,000 BTU window air conditioner units during removal of field heat (USDA, 2013). During regular storage loads only one AC unit will be running (Coolbot, 2014).

In order to determine construction costs, technical drawings were used to determine the quantity and size of lumber required. The area of fiberglass and polystyrene insulation was also calculated. The large room is depicted in Figure 20. Along the walls the cyan is the fiberglass insulation and the magenta is the polystyrene insulation.

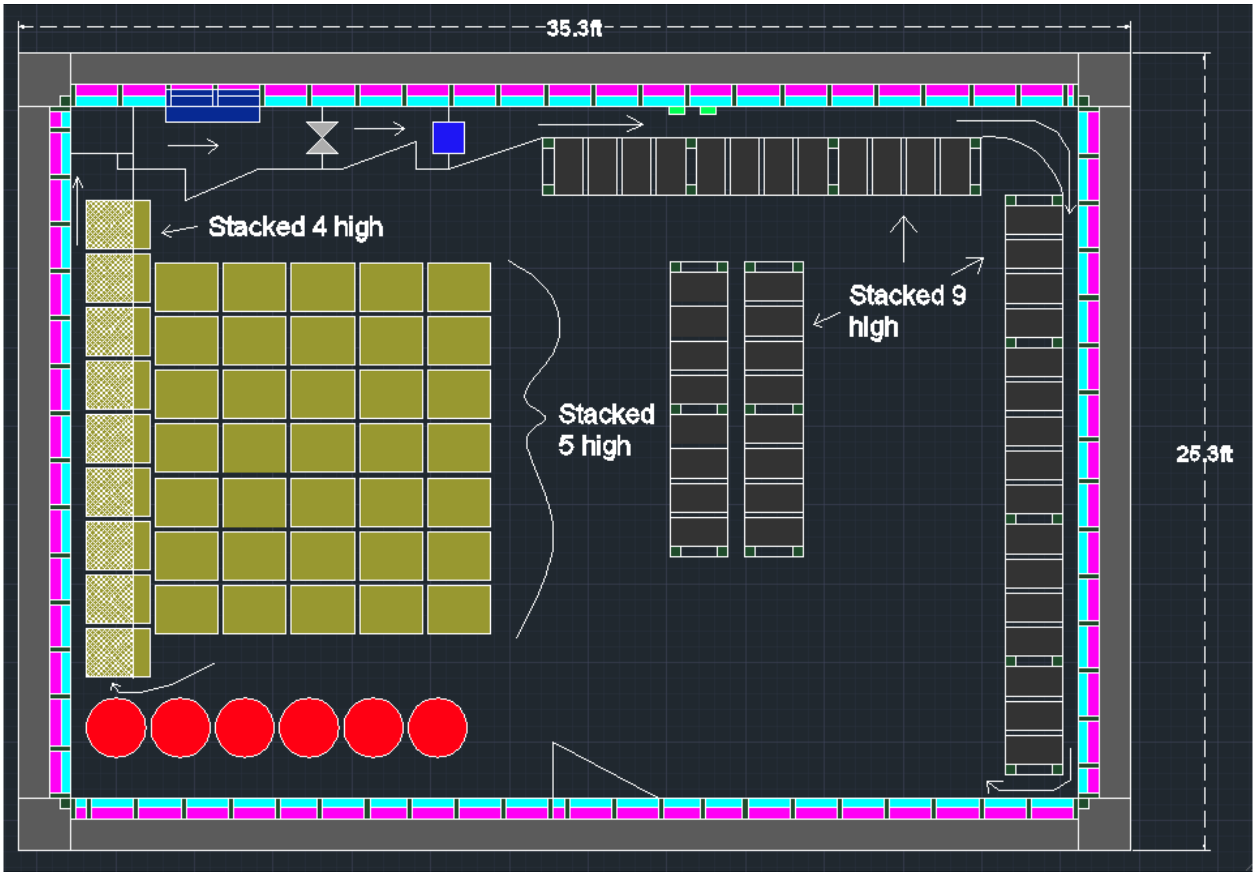

Figure 20: Large room with insulation

The same procedure is performed for the small room, presented in Figure 21.

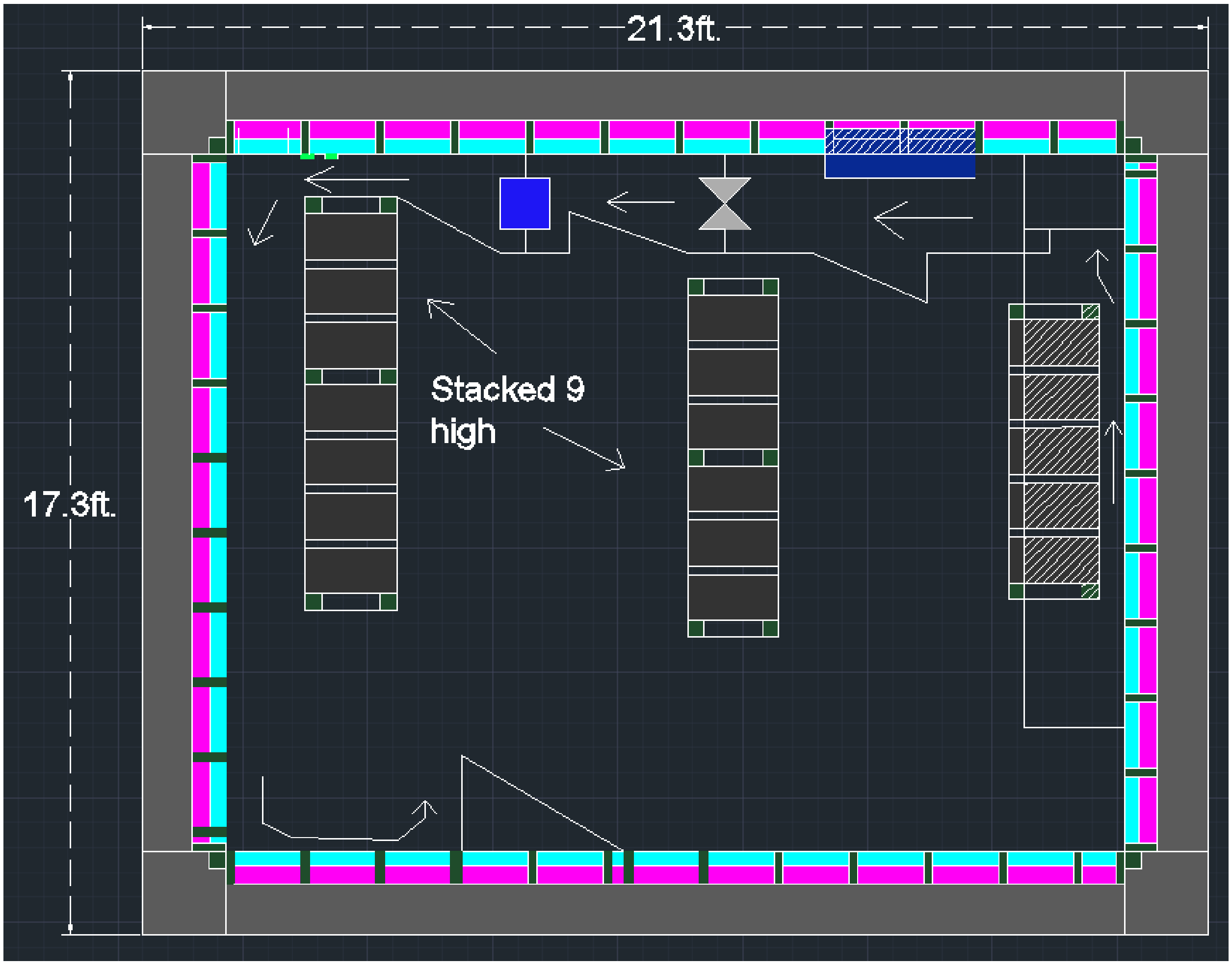

Figure 3: Small room with insulation

Table 19 is an itemized list of all purchases necessary to build the unit, excluding the construction of the basement. This includes the lumber for construction and shelving, the fasteners for construction, the insulation, ventilation, and refrigeration systems. The fans were sourced from Dayton. The lumber and other construction materials were sourced from Home Depot (Home Depot, n.d.)

Table 15: Depicts the pricing for required construction materials

Item	Quantity	Cost	Total Unit Cost
		$	$
LUMBER			
2"x8" – 8'	129	3.48	448.92
2"x8"– 14'	4	10.87	43.48
2"x8"x18'	4	15.97	63.88
4"x4"x8	4	6.77	27.08
2"x8"x22'	4	23.29	93.16
2"x8"x32'	4	45.10	180.40
¾'' 4x8' Exterior Grade Plywood	25	17.26	431.50
½'' 4x8' Plywood Sheathing	38	10.77	409.26
		Subtotal	*1697.68*
SHELVING			
Wood Posts 4"x4"x6'	46	6.99	321.54
Plywood Boards (3/4)"x2'x8'	48	37.25	1,788.00
		Subtotal	*2109.54*
FASTENERS			
Nuts, Bolts, Screws, Nails	Estimate	600.00	600.00
GOOP for sealing	4	7.00	28.00
		Subtotal	*628.00*
INSULATION			
Fiberglass Batt Insulation (3.5"x1.333'x8')	113	4.27	482.00
Extruded Polystyrene Insulation (4"x1.333'x8')	76	31.97	2429.72
		Subtotal	*2911.72*
VENTILATION			
Air Intake	2	30.00	60.00
Direct Drive Axial Fan 150 CFM	1	79.40	79.40
Direct Drive Axial Fan 500 CFM	1	109.95	109.95
Evaporative Cooling Pad 12x6x48in., Pack of 5	1	222.25	222.25
Water Transfer Pump	2	76.96	153.92
Exhaust Vent	2	25.00	50.00
Louvers	2	55.00	110.00
Temperature & RH Sensors	4	80.00	320.00
		Subtotal	*1105.52*
REFRIGERATION			
CoolBot	3	299.00	897.00
15,000 BTU Room AC unit	3	399.00	1197.00
		Subtotal	*2094.00*
Lighting Strips	6	40.00	240.00
Miscellaneous Expenses			1,000.00
		Total	**$11,546.46**

The cost of for both the large and small room alone is estimated to be roughly $11,600. This does not include the construction of the pole barn and the basement. With the fully automated FANCOM system, the total cost is $23,600.

Based on the Seasonal Energy Efficiency Rating (SEER) rating of the selected air conditioner (10.8 BTU/W $\times$ h), the annual electricity usage can be calculated. The calculations assume that the unit is running at full capacity, 24 hours a day, May through July. During the summer months the farmers will be bringing produce in bi-weekly. The unit will be running continuously during these months because of the high outdoor temperatures and the constant influx of people and produce.

For the months of August through November it was assumed the unit is operating proportionally to the heat load. For example, the heat load for August is 5,000 BTU/hr and the unit is designed for 15,000 BTU/hr, it is assumed the unit only has to run 8 hours per day to remove the heat load. Equation 22 describes the ratio

$$\frac{BTU\ required}{BTU\ AC} = \frac{\hbar rs\ AC\ required}{24\ \hbar ours} \qquad \text{(Eq. 22)}$$

However, the first two days of each month are calculated as running continuously in order to remove field heat. December was assumed to be negligible due to the fact that no produce would be added after November, only removed biweekly. Also, cold temperatures will allow the evaporative cooling system to handle the bulk majority of the cooling load. This is assumed throughout the winter months. The A/C unit can be used as a heater if the outdoor temperature places the produce in danger of freezing. The cost of using the A/C as a heater is detailed below.

There are conditions during the winter where heat must be introduced to the unit to prevent freezing. This will not happen if there is a large amount of produce in the room, as they act as “heaters”. However, in case there is a low produce load it may be necessary. It is suggested the farm purchases an A/C unit with heating capability; this will prevent the produce from freezing. A rough calculation was made to determine the cost of this heating. The frost line in Michigan is roughly three and a half feet deep in the soil. Since the unit is eight feet deep, this means that less than half of the walls will be exposed to sub-zero outdoor temperatures. Therefore, only extremely cold outdoor temperatures will cause the unit to freeze. Assuming 20% of the winter meets these temperatures, the A/C unit will need to generate heat for a total of 432 hours during the winter. Between the three A/C units, this will cost an additional $250. Again, this electricity analysis is the worst-case scenario when there is not enough produce in the room to keep the temperature above freezing. This number was generated using the SEER rating calculation outlined below.

The fans in the ventilation system will be running continuously and thus, consuming electricity. The electricity cost of operating the fans can be calculated based on the fan’s watt specifications. The 500 CFM fan is 30 W, and the 239 CFM fan is 26 W. This corresponds to electricity costs of 36.79 $/yr and 31.89 $/yr, respectively.

Therefore the unit is running a total of 3,042 hours. With an air conditioner operating at 15,000 BTU/hr, this equates to 45,630,000 BTU’s. Using the SEER rating shows that this requires 4,225 kWh. Also, there are 3 AC units, so as a high estimate, 12,675 kWh are used in total by the refrigeration system.

The SOF current energy usage due to refrigeration was estimated to be 300,000 kWh per year, which was provided by the client (Walton, 2008). In order to compare the current system to the one designed only May through November electricity savings were looked at. Therefore, only 150,000 kWh are used. Using an electricity rate of 0.14 $/kWh (U.S. Energy Information Administration, 2014), that equates to currently spending $21,000 on refrigeration alone.

Cost of electricity for each month is shown in Figure 22. The total annual cost of electricity is $2,286, accounting for the air conditioning unit, the fans and assuming ten percent for miscellaneous equipment such as lighting. The summer months have the highest cost due to the warm temperatures, and produce is harvested more frequently. Therefore there are more people coming in and out of the cellar, and more field heat to remove. August through November only has produce brought in during the first two days of the month, significantly lowering the operating costs. The fluctuations between August and November are due to temperature differences and produce load.

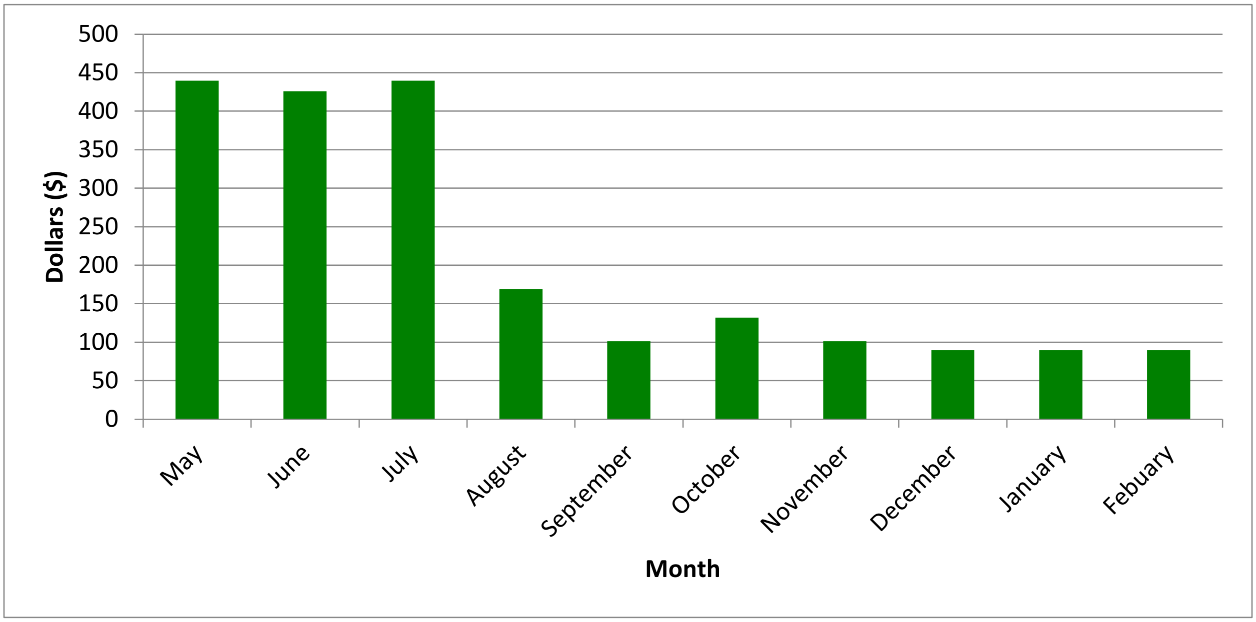

Figure 22: Monthly electricity cost

Construction Methods Cost Analysis

To calculate the cost of construction for the basement, Dr. Welch of the School of Planning, Design, and Construction at Michigan State University was consulted. The cost of using poured concrete and laid blocks are compared.

Although using laid blocks is roughly $2,000 cheaper, Dennis Welch (2014) adamantly suggested that poured concrete should be used in construction due to the strength, quality, and modern construction methods used. Therefore it is recommended using poured concrete in construction of the above ground unit.

For the below ground construction, all costs are taken into consideration except the cost of the ceiling. The excavation size being evaluated is a 56ft x 34ft x 9ft as the building size is

55ft x 34ft x 9ft to allow for extra space for construction needs. The following is the cost comparison of poured concrete vs. laid concrete. For the excavation cost, it is assumed that the soil is mostly clay as the client has indicated and it will not be removed from the site, as there could be a use for it at the SOF. Depending on the hardness of the clay, there could be an increase of up to 60% in the cost of excavation. Table 20 below is a breakdown of a poured concrete basement.

Table 20: Breakdown of poured concrete basement costs

Footings	Unit	Cost ($)
Forming	256 Linear Feet	2,500
Rebar footing	512 Linear Feet +10% for tie	750
Concrete material	19.91 $yard^3$ at $100/$yard^3$	1,990
Placing (chute)	19.91	270
	subtotal	*5,510*
Walls		
Forming	4300 Square Feet of Contract Area	18,300
Concrete material	79.64 $yard^3$ at $106/$yard^3$	8,440
Placing	79.64 $yard^3$	2,400
	subtotal	*29,140*
Floor		
Material	22.4 $yard^3$ at $106/$yard^3$	2,400
Placing	22.4 $yard^3$	390
Finishing	1728 SF	1,050
	subtotal	*3,840*
Excavation		
Combined cost of excavation and labor	635 $yard^3$ at $2.19/$yard^3$	1,390
	subtotal	*1,390*
Total Cost		**39,880**

Table 21 below is a breakdown of the laid concrete costs with excavation. Again this does not take into account the removed of the excavation soil from the site, and that the soil is mostly clay and depending on hardness excavation cost could increase by 60%.

Table 21: Laid concrete blocks cost

Constructed Part	Cost ($)
Walls	27,400
Footings	5,500
Floor	3,800
Excavation	1,390
Total Cost	**38,090**

Again it is recommended that the client use poured concrete instead of laid blocks even though the cost of laid blocks is roughly $1,500 cheaper. This is due to current construction practices and recommendations by Dennis Welch.

Comparison of Above and Below Ground Cold Storage Units

The client requested a comparison of an above and below ground cold storage unit. The reasoning behind this is that he wanted to make an educated decision on if the SOF should invest in building a below ground unit to harness the cooler temperature of the soil or invest in a highly insulated energy efficient above ground storage unit.

The above ground unit selected is a modularly constructed metal panel room fabricated by the Michigan company, Eagle Enterprise. The company sells and fully assembles insulated metal panels (R=34) for cold storage. The ventilation and refrigeration systems will need to be installed in the unit. This unit will be placed in a corner of the pole barn. This unit will save money on lumber, insulation, concrete and excavation costs. However, the cost of electricity will increase due to the heat conduction gain. These savings and losses will be analyzed. The total cost for the modulated above ground unit was quoted at $33,340. This is much cheaper than the original estimate of the basement of $51,260.

A comparison between the modulated-above ground and belowground units AC load needed to cool the unit was used to calculate electricity requirements between the two units. This comparison is shown in Table 22. August was chosen because it is the month where the temperature difference between the outside air and the room temperature is the largest and shows the greatest difference in heat conduction between the above ground and below ground units. Notice that the differences between above and below ground units are not large enough to change the A/C unit size required. Therefore, the differences are insignificant, around $250/year.

Table 22: Above ground and below ground AC load

	Below Ground unit	**Modulated Above Ground Unit**
Total Heat Conduction cold room (BTU/hr)	2,518	3,117
Total heat load (BTU/hr)*	14,322	14,981
AC load (Tons AC)	1.193	1.248
Total heat load after field heat removal (BTU/hr)	5,214	5,873
AC load (Tons AC)	0.434	0.489
Total Heat Conduction cool room (BTU/hr)	778	963
Total heat load (BTU/hr)	9,427	9,631
AC load (Tons AC)	0.786	0.803
Total heat load after field heat removal (BTU/hr)	2,185	2,389
AC load (Tons AC)	0.182	0.200
Highest AC load (Tons AC)	**1.193**	**1.248**

*Assuming cabbage and garlic don't come in on the same day and these calculations do not take into the effect of evaporative cooling

The thinking behind basement cellars is that the cooling temperature of the soil will greatly reduce the conductive heat load. However, when high R-value insulation is used, this difference is negligible. The maximum AC load for the below ground unit is 1.193 while the max AC load for the above ground unit is 1.248. This means building above ground increases the heat load by only five percent. This five percent difference is miniscule enough that the AC unit is sized the same for above and below ground. However, the load on the AC unit will be slightly lower, resulting in a subtle reduction in electricity costs. Essentially, building below ground is great for a passive system, but is unnecessary for an engineered system.

One reason that the aboveground and belowground conduction differences are so small is that only three walls are in contact with the outside conditions. Another reason the above ground unit has a similar AC loads is due to the fact that conduction through the walls is only about 10-15% of the total heat load. Therefore, it has a low impact on the overall heat load. Focusing on reducing the field heat will have a greater impact on electricity use than minimizing conduction.

A final reason for the similar AC load is due to the very high R-value used for both the above ground and below ground units. A high R-value cuts down on the heat conduction substantially. As shown in Table 23 and Figure 23 smaller R-values results in a much higher heat conduction difference. The significance of the cool soil is demonstrated by calculating the effect with a lower R-value.

Table 23: The effect of R-value on conduction

R Value	**Conduction of the Below Ground Large Room**	**Conduction of the Modulated Above Ground Large Room**
	BTU/hr	*BTU/hr*
34.28	2,518	3,117
30	2,745	3,401
25	3,105	3,856
15	4,502	5,676
10	6,182	7,950

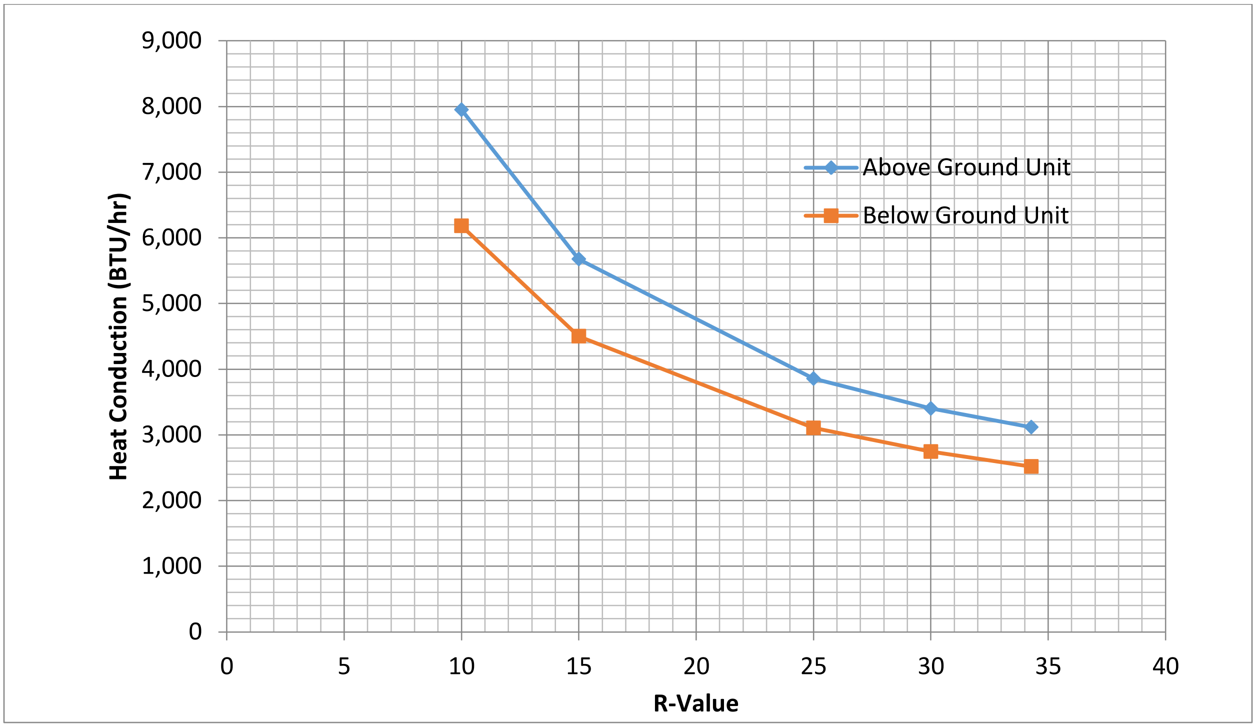

Figure 23: R-value vs. Heat conduction trend in the above ground and below ground units

Due to the high R-value used in the storage, the savings in conduction by building underground are quite small. However, the cost to construct aboveground is 35% cheaper. This comparison leads to the conclusion that the client should buy a modular metal panel room instead of building a basement.

Ownership Economics

In order to provide an understanding of the economics surrounding the ownership of the various components, an annual cost for the storage unit structure, the equipment in the unit, and the building housing the unit was conducted. Equations 23 through 30 were used to calculate annual cost.

$$\text{Salvage Value} = 20\% \times \text{Purchase Price} \qquad \text{(Eq. 23)}$$

$$\text{Calculated Average Investment} = \frac{\text{Purchasing Price} + \text{Salvage Value}}{2} \qquad \text{(Eq. 24)}$$

$$\text{Straight Line Depreciation} = \frac{\text{Purchase Price} - \text{Salvage Value}}{\text{Expected Economic Life}} \qquad \text{(Eq. 25)}$$

$$\text{Real Interest Rate} = \text{Nominal Rate} - \text{Inflation Rate} \qquad \text{(Eq. 26)}$$

$$\text{Interest} = \text{Interest Rate} \times \text{Calculated Average Investment} \qquad \text{(Eq. 27)}$$

$$\text{Insurance} = .5\% \times \text{Purchase Price} \qquad \text{(Eq. 28)}$$

$$\text{Repair \& Maintenance} = 3\% \times \text{Purchase Price} \qquad \text{(Eq. 29)}$$

$$\text{Annual Cost} = \text{Straight Line Depreciation} + \text{Interest} + \text{Insurance} + \text{Repair \& Maintenance} \quad \text{(Eq. 30)}$$

Labor is included in the purchase price of the building. A breakdown of the annual cost can be found in Table 24.

Table 24: Breakdown of cost in storage rooms

	Units	Below Ground Unit	Modulated Above Ground Unit	Equipment
Purchase Price	$	51,260	33,340	3,410
Expected Economic Life	yr	20	20	7
Interest Rate	%	0.04	0.04	0.04
Salvage Value	$	10,252	6,680	0
Calculated Average Investment	$	30,756	20,004	1,705
Straight Line Depreciation	$/yr	2,051	1,334	488
Interest	$/yr	1,231	801	69
Insurance	$/yr	257	167	18
Repair & Maintenance	$/yr	42	27	49
Annual Cost	$/yr	*3,578*	*2,238*	*624*

Solar Energy Analysis

Dr. Biernbaum expressed in various conversations his interest in renewable energy, particularly, solar power. He also noted that there is a limited amount of power available to the planned pole barn location, and that an upgrade would be costly. For these reasons, the Local Roots contacted Mark Hagerty of Michigan Solar Solutions to design and quote a photovoltaic solar panel system to be installed on the roof of the pole barn. The system was designed to provide 20,160 kWh per year, enough to power the cold storage unit with additional capacity to run classroom appliances.

To generate this much power, the farm would need 60 -280W SunModule solar panels, available from SolarWorld. These panels would be best arranged on the South roof of the barn, in 3 rows of 20 panels. Additionally, there is the need for Enphase micro-inverters to quickly convert the DC current to AC, greatly reducing power loss. Both the panels and inverters come with a 25-year warranty, and the panels are virtually indestructible. The total cost for the system is $54,600 for a minimum of 25 years of sustainable cold storage.

Throughout the year, the majority of the power generated falls between Spring and Fall. Conveniently, the cold storage unit will consume the most electricity in this same window. However, there is a Michigan law stating that the excess electricity must be bought back by the grid in exchange for full retail credit. This means that the farm can use their credits in the winter or on cloudy days. The client may also want to investigate whether this law will enable the SOF to get a free power line dug to the pole barn by the electrical company.

To put the system in perspective, the cost to buy this much electricity at the current rate ($.14/kWh) for 25 years was calculated. This cost is $70,560. This means that the farm will save a minimum of $15,960 on electricity over the 25-year warranty period, or $640/yr. Additionally, the price of electricity from the grid is very likely to rise in the next 25 years, and, the equipment may last well beyond 25 years. Finally, installing solar energy will align with the SOF philosophy, and even become a source of pride for the farm and the newly constructed pole barn.

Payback Period

The payback period is calculated by the total cost divided by yearly savings. For the basement unit, the total cost is $51,260 and the above ground total cost is $33,340. With annual savings of $19,226, the payback period for the aboveground unit with a FANCOM system is 2.4

years. The payback period for the basement unit with a FANCOM system is 3.3 years. In reality, the payback period would be even longer because the cost of building the basement ceiling was ignored. Finally, the total cost for an aboveground unit with a FANCOM system that is powered by solar would cost $100,000 and have a 5 year payback period.

Future Considerations

After researching cold storage for several months the Local Roots team has several suggestions for the SOF in order to reduce the heat load. First of all, produce should be harvested at night or very early in the morning. This minimizes the temperature of incoming produce and allows quicker removal of field heat. Harvesting at night will greatly reduce operating costs and improve produce quality. Also, harvest should be spread out over several days in order to reduce the load on the system.

Once the produce is brought into the room, it is wise to store it as close to the ventilation system as possible. The cool air from the ventilation grate will help quickly cool the produce. Also, it is recommended to drill holes in the crates and notes, in order to increase air infiltration during cooling.

Conclusion

The client's initial goal was to design an energy efficient cold storage unit that could store a wide range of produce at a reduced energy cost when compared to the existing refrigeration system. The SOF is currently planning to build a pole barn but the client questioned if it would be better to build a basement utilizing the cooling effects of the soil, or an above ground unit with a high R-value.

According to this analysis both the above and below ground units can both store the entire range of produce as well as decrease the amount of electricity used compared to present consumption. Based on all of the data, it was concluded that the modulated above ground cold storage unit was the unit that the client should invest in. It was calculated that the basement option did not save as much on electricity, $250 per year, as originally assumed. This was a result of the high R-value used in the analysis. High R-values reduce the cooling effect of the soil. In addition the capital cost to build a basement is approximately $17,920 more than the modulated above ground unit. Also, the annual cost to run the basement unit was $1,340 more per year than the modulated above ground unit. Based on the cost differential between the modulated above ground cold storage unit and the below ground unit, it would be best for the SOF to build a modulated above ground unit.

The payback period for a fully functional modulated cooling unit, with the FANCOM system included was calculated to be 2.4 years, well within the original goal of less than 4 years. If the SOF wanted to become even greener, the analysis also provided the use of solar energy to power the cold storage unit. The payback period with the functional unit and the solar panels would be approximately 5 years. This is more than the original goal of 4 years, but the solar panels could also provide the SOF with additional revenue if the panels generate more electricity than is needed to run the cooling unit.

As requested, the analysis provides multiple alternatives that the client can chose from. Thank you for the opportunity to work with you.

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Appendix A

See attached Excel file to view the remaining calculations including: heat of respiration, heat field, total heat conduction loss, and service load.

Respiration:

$$\text{Beets } Q_{HR}:\ 3500\,lbs \times 1.10\frac{Btu}{lb \times 24hrs} \times 24hr = 92400\frac{Btu}{hr}$$

Heat Field:

$$\text{Beets } Q_{HF}:\ 3500\,lbs \times 0.9\frac{Btu}{lbs \times {}^{\circ}F \times hr} \times (81^{\circ}F - 32^{\circ}F) = 154350\frac{Bt}{hr}$$

Appendix B

Below is calculations of the weight and storage size of the produce.

	A	B	C	D	E	F	G	H
1	**Container Volume**							
2	*Length (ft)*	2						
3	*Width (ft)*	1.5						
4	*Height (ft)*	0.75						
5	*Total Volume (ft^3)*	2.25						
6								
7	**Estimated "fullness"**	0.75						
8								
9								
10	**Produce**	**Cold or Cool**	**Weight**	**bulk density**	**Volume**	**Storage containers (Volume* Estimated "fullness")**	**Produce in storage container**	
11			*lbs*	*lbs/ft^3*	*ft^3*	*ft^3*	*containers*	*containers*
12	*Beets*	cold	3500	35.89	97.52	1.69	57.79	58
13	*Cabbage*	cold	4500	23.48	191.65	1.69	113.57	114
14	*Carrots*	cold	6000	33.78	177.62	1.69	105.26	106
15	*Celeriac*	cold	1000	41.16	24.30	1.69	14.40	15
16	*Garlic*	cold	750	35.89	20.90	1.69	12.38	13
17	*Onions*	cold	3000	42.22	71.06	1.69	42.11	43
18	*Rutabagas*	cold	1500	36.94	40.61	1.69	24.06	25
19	*Potatoes-Mature*	cool	7000	39.58	176.86	1.69	104.80	105
20	*Winter Squash*	cool	5000	30.61	163.35	1.69	96.80	97
21								
22	**Sum**				963.85			576
23	Cold		20250					
24	Cool		12000				**Volume of Containers (ft^3)**	1296
25	*Total*		32250					
26								
27	**Clients dimentions of basement**							
28	Lenght (ft)	55						
29	Width (ft)	30						
30	Heirght (ft)	8						
31	*Volume of Basement (ft^3)*	13200						
32								
33								

Figure 4: Calculations of the weight and storage size of the produce

Appendix C

Consists of the Work Break-down Structure in list form and a Gantt chart in a graphic form. This was completed using Microsoft Project. A full copy can also be found as an attached Microsoft Project document.

		Task Mode	Task Name	Duration	Start	Finish	Predecessors	Resource Names	Work	% Work Complete
21	✓		Meet with Faculty Advisor and Client	0.38 days	Fri 10/18/13	Fri 10/18/13	20	Drew,John,Robby	3 hrs	100%
22	✓		Work on TP#2	3 days	Sat 10/19/13	Tue 10/22/13		John,Robby	6 hrs	100%
23	✓		Give TP#2	0.03 days	Wed 10/23/13	Wed 10/23/13	22	Drew,John,Robby	0.75 hrs	100%
24	✓		Change TP#2 from immediate feedback	2 days	Wed 10/23/13	Thu 10/24/13	23	Drew,John,Robby	4 hrs	100%
25	✓		Visit Titus Farms with Dr. Biernbaum	0.56 days	Wed 10/23/13	Wed 10/23/13		Drew,John,Robby	4.5 hrs	100%
26	✓		Presentaiton to BAE Industry Advisory Board	0.03 days	Fri 10/25/13	Fri 10/25/13	24	Drew,John,Robby	0.75 hrs	100%
27	✓		Meet with Drs. Kirk and Reese to discuss project	0.06 days	Fri 10/25/13	Fri 10/25/13	26	Drew,John,Robby	0.5 hrs	100%
28			Work on WBS	1 day	Mon 10/28/13	Mon 10/28/13	27	Drew	8 hrs	90%
29			Work on Budget	1 day	Mon 10/28/13	Mon 10/28/13	27	Robby	3 hrs	90%
30			Add Budget and WBS to DL#4	1 day	Tue 10/29/13	Tue 10/29/13	28,29	Drew,John,Robby	0.1 hrs	0%
31			Make changes to DL#4 from DL#3 suggestions	1 day	Tue 10/29/13	Tue 10/29/13		Drew,John,Robby	8 hrs	0%
32			Turn in DL#4	0 days	Wed 10/30/13	Wed 10/30/13	30,31	Drew,John,Robby	0 hrs	0%
33			Turn in TL#4	0 days	Wed 10/30/13	Wed 10/30/13		Drew,John,Robby	0 hrs	0%
34			Finalize necessary produce characteristics (specific heat, density, heat of respiration, latent heat, storage condition, shelf life, relative humidites, evapo rates, transpiration rates etc)	1 day	Mon 10/28/13	Mon 10/28/13		Drew,John,Robby	6 hrs	80%
35			Calculate: q needed to cool produce from ambient to storage temp	25 days	Tue 10/29/13	Sat 11/30/13	34	Drew,John,Robby	10 hrs	50%
36			Calculate: q generated through respiration in produce	25 days	Tue 10/29/13	Sat 11/30/13	34	Drew,John,Robby	10 hrs	50%
37			Calculate: h20 generated through transpiration	25 days	Tue 10/29/13	Sat 11/30/13	34	Drew,John,Robby	10 hrs	50%
38			Calculate: CO2/Ethylene generated	25 days	Tue 10/29/13	Sat 11/30/13	34	Drew,John,Robby	10 hrs	50%
39			Input for crate size, %	26 days	Mon 10/28/13	Sat 11/30/13		John,Robby	10 hrs	75%

eady New Tasks : Manually Scheduled

Figure 5: Depicts a sample of the WBS, a full copy can be found in the attached Microsoft Project file

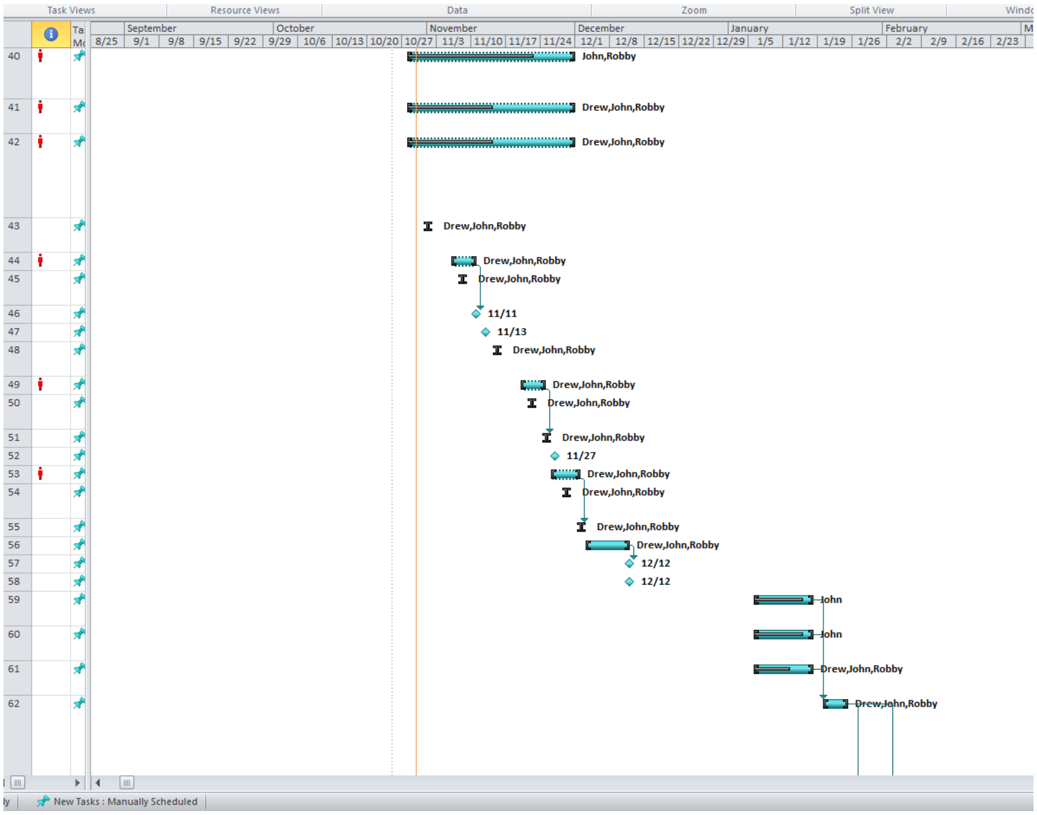

Figure 6: Sample of the Gantt chart, a full copy can be found in the attached Microsoft Project file